

EXISTENCE OF WEAK SOLUTIONS FOR THE GENERALIZED NAVIER-STOKES EQUATIONS WITH DAMPING

H.B. DE OLIVEIRA*,**

**FCT - Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal*

***CMAF - Universidade de Lisboa, Av. Prof. Gama Pinto, 2, 1649-003 Lisboa, Portugal.*

ABSTRACT. In this work we consider the generalized Navier-Stokes equations with the presence of a damping term in the momentum equation. The problem studied here derives from the set of equations which govern the isothermal flow of incompressible, homogeneous and non-Newtonian fluids. For the generalized Navier-Stokes problem with damping, we prove the existence of weak solutions by using regularization techniques, the theory of monotone operators and compactness arguments together with the local decomposition of the pressure and the Lipschitz-truncation method. The existence result proved here holds for any $q > \frac{2N}{N+2}$ and any $\sigma > 1$, where q is the exponent of the diffusion term and σ is the exponent which characterizes the damping term.

Keywords and phrases: generalized Navier-Stokes, damping, existence of weak solutions, decomposition of the pressure, Lipschitz truncation.

MSC 2010: 35D05, 35K55, 35Q30, 76D03, 76D05.

1. INTRODUCTION

In this work, we shall study the existence of weak solutions for the generalized Navier-Stokes equations with damping:

$$(1.1) \quad \operatorname{div} \mathbf{u} = 0 \quad \text{in } Q_T,$$

$$(1.2) \quad \frac{\partial \mathbf{u}}{\partial t} - \operatorname{div} (|\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u} - \mathbf{u} \otimes \mathbf{u}) + \alpha |\mathbf{u}|^{\sigma-2} \mathbf{u} = \mathbf{f} - \nabla p \quad \text{in } Q_T;$$

supplemented with the following initial and boundary conditions:

$$(1.3) \quad \mathbf{u} = \mathbf{u}_0 \quad \text{in } \Omega \quad \text{for } t = 0,$$

$$(1.4) \quad \mathbf{u} = \mathbf{0} \quad \text{on } \Gamma_T.$$

Here Q_T is a general cylinder defined by

$$Q_T := \Omega \times (0, T), \quad \text{with } \Gamma_T := \partial\Omega \times (0, T),$$

E-mail address: holivei@ualg.pt.

Date: September 23, 2011.

The author's work was supported by the grant SFRH/BSAB/1058/2010, MCTES, Portugal, and by the research project PTDC/MAT/110613/2010, FCT, Portugal.

where $\Omega \subset \mathbb{R}^N$, $N \geq 2$, is a bounded domain with a compact boundary $\partial\Omega$, and $0 < T < \infty$.

In the scope of Mathematical Fluid Mechanics, \mathbf{u} is the velocity field, p stands for the pressure divided by the constant density, \mathbf{f} is the given forcing term and $q > 1$ is the constant exponent which characterizes the flow. The constant α is non-negative and $\sigma > 1$ is another constant.

The damping term $\alpha|\mathbf{u}|^{\sigma-2}\mathbf{u}$, or sometimes called absorption term, has no direct physical justification in Fluid Mechanics, although it might be considered has being part of the external body forces field (see [1]–[3]). There is also a precise theory of the absorption of forced plane infinitesimal waves according to the Navier-Stokes equations (see [23]). The consideration of damping terms in the generalized Navier-Stokes equations it is also useful as a regularization procedure to prove the existence of weak solutions for the stationary problems (see [13]–[14]). At last, but not in last, there is also the purely mathematical motivation which goes back to a work about a stationary like problem (see [8]), where the authors where mainly interested with the important question about compact supported solutions for that problem. During the last years, many authors have worked on these kind of modified Navier-Stokes type problems, establishing the existence of weak solutions and proving many other properties has the uniqueness of weak solutions, their regularity and studying its asymptotic behavior. In [18] we proved the weak solutions of (1.1)–(1.4) extinct in a finite time for $q \geq 2$, provided $1 < \sigma < 2$. This property is well known for the generalized Navier-Stokes problem (1.1)–(1.4) with $\alpha = 0$ in the case $1 < q < 2$. But for $q \geq 2$ the best one can gets are some decays of fractional and exponential order (see *e.g.* [7]). In [4] we have studied the problem (1.1)–(1.4) in the particular case of $q = 2$. There, we have proved the existence of weak solutions, its uniqueness and some asymptotic properties. We carried out an analogous study in [5] for the Oberbeck-Boussinesq version of this problem, where besides the usual coupling in the buoyancy force, we have considered an extra coupling in the damping term by considering a temperature-depending function σ . In [10] the authors have proved the existence of weak and strong solutions for the Cauchy problem (1.1)–(1.4) in \mathbb{R}^3 and with $q = 2$. The damping term is being considered in the context of many other physical systems which go from the Shrödinger equations (see *e.g.* [11]) to the Euler equations (see *e.g.* [19]) and passing by the wave equation (see *e.g.* [26]).

With respect to the existence of weak solutions for the original generalized Navier-Stokes problem, *i.e.* (1.1)–(1.4) with $\alpha = 0$, the problem was solved in its all full possible (it is open only the case $1 < q < \frac{2N}{N+2}$) extension recently in the work [12]. The first existence result to this problem was achieved in [16] and [17] for $q \geq \frac{3N+2}{N+2}$. Only more or less 40 years later it was possible to improve the existence result for lower values of q . In [25], under the same assumptions of [16] and [17], it was proved the existence of weak solutions to the problem (1.1)–(1.4) with $\alpha = 0$ for $q \geq \max \left\{ \frac{3N}{N+2}, \frac{N+\sqrt{3N^2+4N}}{N+2} \right\}$. A lit bit earlier to the work [25], it was proved in [24] the existence of a weak solution to the same problem for $q > 2\frac{N+1}{N+2}$. Finally in [12] the authors have extended the result [24] to the case $q > \frac{2N}{N+2}$. It is an open problem to prove the existence of weak solutions to the problem (1.1)–(1.4) with $\alpha = 0$ if $1 < q \leq \frac{2N}{N+2}$ in the case of $N > 2$. On the other hand, it seems to be very difficult to go bellow the limit $q = \frac{2N}{N+2}$ (for $N > 2$), due to the need of using the compact imbedding $\mathbf{W}^{1,q}(\Omega) \hookrightarrow \mathbf{L}^2(\Omega)$.

The plan of this work is the following. In Section 1 we introduce the problem we shall study here and review some results related with our work. Section 2 is devoted to introduce the notation we use throughout the work and to define the notion of weak solution we shall consider. Here, we also shall state the main result of this paper: Theorem 2.1. The proof of this result is carried out from Section 3 to Section 11. In Section 12, we make some remarks about our work, in special, its extensions and limitations.

2. WEAK FORMULATION

The notation used throughout this article is largely standard in Mathematical Fluid Mechanics - see *e.g.* [17]. We distinguish tensors and vectors from scalars by using boldface letters. For functions and function spaces we will use this distinction as well. The symbol C will denote a generic constant - generally a positive one, whose value will not be specified; it can change from one inequality to another. The dependence of C on other constants or parameters will always be clear from the exposition. In this paper, the notations Ω or ω stand always for a domain, *i.e.*, a connected open subset of \mathbb{R}^N , $N \geq 1$. By $\mathcal{L}_N(\omega)$ we denote the N -dimensional Lebesgue measure of ω . Given $k \in \mathbb{N}$, we denote by $C^k(\Omega)$ the space of all k -differentiable functions in Ω . By $C_0^\infty(\Omega)$ or $\mathcal{D}(\Omega)$, we denote the space of all infinity-differentiable functions with compact support in Ω . The space of distributions over $\mathcal{D}(\Omega)$ is denoted by $\mathcal{D}'(\Omega)$. If X is a generic Banach space, its dual space is denoted by X' . Let $1 \leq q \leq \infty$ and $\Omega \subset \mathbb{R}^N$, with $N \geq 1$, be a domain. We will use the classical Lebesgue spaces $L^q(\Omega)$, whose norm is denoted by $\|\cdot\|_{L^q(\Omega)}$. For any nonnegative k , $W^{k,q}(\Omega)$ denotes the Sobolev space of all functions $u \in L^q(\Omega)$ such that the weak derivatives $D^\alpha u$ exist, in the generalized sense, and are in $L^q(\Omega)$ for any multi-index α such that $0 \leq |\alpha| \leq k$. The norm in $W^{k,q}(\Omega)$ is denoted by $\|\cdot\|_{W^{k,q}(\Omega)}$. The corresponding spaces of vector-valued or tensor-valued functions are denoted by boldface letters. All these spaces are Banach spaces and the Hilbert framework corresponds to $q = 2$. In the last case, we use the abbreviation $W^{k,2} = H^k$. Given $T > 0$ and a Banach space X , $L^q(0, T; X)$ and $W^{k,q}(0, T; X)$ denote the usual Bochner spaces used in evolutive problems, with norms denoted by $\|\cdot\|_{L^q(0, T; X)}$ and $\|\cdot\|_{W^{k,q}(0, T; X)}$. By $C_w([0, T]; X)$ we denote the subspace of $L^\infty(0, T; X)$ consisting of functions which are weakly continuous from $[0, T]$ into X .

A very important property satisfied by the tensor $\mathbf{S} = |\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u}$ and by the damping term $|\mathbf{u}|^{\sigma-2} \mathbf{u}$ are expressed in the following lemma which proof we address the reader to [6].

Lemma 2.1. *For all $s \in (1, \infty)$ and $\delta \geq 0$, there exist constants C_1 and C_2 , depending on s and N , such that for all $\xi, \eta \in \mathbb{R}^N$, $N \geq 1$,*

$$(2.5) \quad (|\xi|^{s-2} \xi - |\eta|^{s-2} \eta) \cdot (\xi - \eta) \geq C_2 |\xi - \eta|^{2+\delta} (|\xi| + |\eta|)^{s-2-\delta}.$$

In order to define the notion of weak solutions we shall look for, let us introduce the usual functional setting of Mathematical Fluid Mechanics:

$$(2.6) \quad \mathcal{V} := \{\mathbf{v} \in C_0^\infty(\Omega) : \operatorname{div} \mathbf{v} = 0\};$$

$$(2.7) \quad \mathbf{H} := \text{closure of } \mathcal{V} \text{ in } \mathbf{L}^2(\Omega);$$

$$(2.8) \quad \mathbf{V}_q := \text{closure of } \mathcal{V} \text{ in } \mathbf{W}^{1,q}(\Omega).$$

The weak solutions we are interested in are usually called in the sense of Leray-Hopf.

Definition 2.1. *Let $N \geq 2$ and $1 < q, \sigma < \infty$. Assume that $\mathbf{u}_0 \in \mathbf{H}$, $\mathbf{f} \in \mathbf{L}^1(Q_T)$ and let conditions (A)-(D) be fulfilled for any $q > 1$. A vector field \mathbf{u} is a weak solution to the problem (1.1)-(1.4), if:*

- (1) $\mathbf{u} \in \mathbf{L}^\infty(0, T; \mathbf{H}) \cap \mathbf{L}^q(0, T; \mathbf{V}_q) \cap \mathbf{L}^\sigma(Q_T)$;
- (2) For every $\varphi \in \mathbf{C}^\infty(Q_T)$, with $\operatorname{div} \varphi = 0$ and $\operatorname{supp} \varphi \subset \subset \Omega \times [0, T)$,

$$\begin{aligned} & - \int_{Q_T} \mathbf{u} \cdot \varphi_t \, dxdt + \int_{Q_T} (|\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u} - \mathbf{u} \otimes \mathbf{u}) : \nabla \varphi \, dxdt + \alpha \int_{Q_T} |\mathbf{u}|^{\sigma-2} \mathbf{u} \cdot \varphi \, dxdt \\ & = \int_{Q_T} \mathbf{f} \cdot \varphi \, dxdt + \int_{\Omega} \mathbf{u}_0 \cdot \varphi(0) \, dx. \end{aligned}$$

Remark 2.1. Note that $\mathbf{V}_q \hookrightarrow \mathbf{L}^\sigma(\Omega)$ for $\sigma \leq q^*$, where q^* is the Sobolev conjugate of q , i.e. $q^* = \frac{Nq}{N-q}$ if $1 < q < N$, or $q^* = \infty$ if $q \geq N$. Therefore, in this case, we look for weak solutions in the class $\mathbf{L}^\infty(0, T; \mathbf{H}) \cap \mathbf{L}^q(0, T; \mathbf{V}_q)$.

The main result of this work is the following, where it is established the existence of weak solutions to the problem (1.1)-(1.4) under the minor possible assumptions on q and σ . We left open only the case of $1 < q \leq \frac{2N}{N+2}$, for $N > 2$, which will certainly require a different approach.

Theorem 2.1. *Let Ω be a bounded domain in \mathbb{R}^N , $N \geq 2$, with a Lipschitz-continuous boundary $\partial\Omega$. Assume that*

$$(2.9) \quad \mathbf{f} \in \mathbf{L}^{q'}(0, T; \mathbf{V}'_q),$$

$$(2.10) \quad \mathbf{u}_0 \in \mathbf{H}.$$

Then, if

$$(2.11) \quad q > \frac{2N}{N+2},$$

there exists a weak solution to the problem (1.1)-(1.4), in the sense of Definition 2.1, for any $\sigma > 1$. Moreover, any weak solution $\mathbf{u} \in \mathbf{C}_w([0, T]; \mathbf{H})$.

In order to simplify the exposition, we shall assume throughout the rest of this work the following simplified assumption of (2.9)

$$(2.12) \quad \mathbf{f} = -\operatorname{div} \mathbf{F}, \quad \mathbf{F} \in \mathbf{L}^{q'}(Q_T).$$

The main ingredients of the proof of Theorem 2.1 are the results of the local decomposition of the pressure established in [24] and the Lipschitz-truncation method in the spirit of [12]. We could also have considered the \mathbf{L}^∞ -truncation method used in [24], but by this method we cannot achieve an existence result for so lower values of q as we can with the Lipschitz-truncation method. The proof of Theorem 2.1 will be the aim of the next sections.

3. THE REGULARIZED PROBLEM

We start the proof of Theorem 2.1 by considering a regularization of the problem (1.1)-(1.4) which basically gets rid off the difficulties coming from the convective term $\mathbf{u} \otimes \mathbf{u}$. Let $\Phi \in \mathbf{C}^\infty([0, \infty))$ be a non-increasing function such that $0 \leq \Phi \leq 1$ in $[0, \infty)$, $\Phi \equiv 1$ in $[0, 1]$, $\Phi \equiv 0$ in $[2, \infty)$ and $0 \leq -\Phi' \leq 2$. For $\epsilon > 0$, we set

$$(3.13) \quad \Phi_\epsilon(s) := \Phi(\epsilon s), \quad s \in [0, \infty),$$

and let us consider the following regularized problem:

$$(3.14) \quad \operatorname{div} \mathbf{u}_\epsilon = 0 \quad \text{in } Q_T,$$

$$(3.15)$$

$$\frac{\partial \mathbf{u}_\epsilon}{\partial t} - \operatorname{div} (|\nabla \mathbf{u}_\epsilon|^{q-2} \nabla \mathbf{u}_\epsilon - \mathbf{u}_\epsilon \otimes \mathbf{u}_\epsilon \Phi_\epsilon(|\mathbf{u}_\epsilon|)) + \alpha |\mathbf{u}_\epsilon|^{\sigma-2} \mathbf{u}_\epsilon = \mathbf{f} - \nabla p_\epsilon, \quad \text{in } Q_T,$$

$$(3.16) \quad \mathbf{u}_\epsilon = \mathbf{u}_0 \quad \text{in } \Omega \quad \text{for } t = 0,$$

$$(3.17) \quad \mathbf{u}_\epsilon = \mathbf{0} \quad \text{on } \Gamma_T.$$

A vector function $\mathbf{u}_\epsilon \in L^\infty(0, T; \mathbf{H}) \cap L^q(0, T; \mathbf{V}_q) \cap \mathbf{L}^\sigma(Q_T)$ is a weak solution to the problem (3.14)-(3.17), if

$$(3.18) \quad \begin{aligned} & - \int_{Q_T} \mathbf{u}_\epsilon \cdot \varphi_t \, d\mathbf{x} dt + \int_{Q_T} (|\nabla \mathbf{u}_\epsilon|^{q-2} \nabla \mathbf{u}_\epsilon - \mathbf{u}_\epsilon \otimes \mathbf{u}_\epsilon \Phi_\epsilon(|\mathbf{u}_\epsilon|)) : \nabla \varphi \, d\mathbf{x} dt \\ & + \alpha \int_{Q_T} |\mathbf{u}_\epsilon|^{\sigma-2} \mathbf{u}_\epsilon \cdot \varphi \, d\mathbf{x} dt = \int_{Q_T} \mathbf{F} : \nabla \varphi \, d\mathbf{x} dt + \int_{\Omega} \mathbf{u}_0 \cdot \varphi(0) \, d\mathbf{x} \end{aligned}$$

for all $\varphi \in \mathbf{C}^\infty(Q_T)$, with $\operatorname{div} \varphi = 0$ and $\operatorname{supp} \varphi \subset \subset \Omega \times [0, T]$.

Proposition 3.1. *Let the assumptions of Theorem 2.1 be fulfilled. Then, for each $\epsilon > 0$, there exists a weak solution $\mathbf{u}_\epsilon \in L^q(0, T; \mathbf{V}_q) \cap C_w([0, T]; \mathbf{H}) \cap \mathbf{L}^\sigma(Q_T)$ to the problem (3.14)-(3.17). In addition, every weak solution satisfies to the following energy equality:*

$$(3.19) \quad \frac{1}{2} \|\mathbf{u}_\epsilon(t)\|_{\mathbf{H}}^2 + \int_{Q_t} |\nabla \mathbf{u}_\epsilon|^q \, d\mathbf{x} dt + \alpha \int_{Q_t} |\mathbf{u}_\epsilon|^\sigma \, d\mathbf{x} dt = \frac{1}{2} \|\mathbf{u}_0\|_{\mathbf{H}}^2 + \int_{Q_t} \mathbf{F} : \nabla \mathbf{u}_\epsilon \, d\mathbf{x} dt$$

for all $t \in (0, T)$.

Proof. The proof of Proposition 3.1 is adapted from the proof of [24, Theorem 3.1]. The difference here is the presence of an extra term which results from the damping and the aspect of the diffusion term. We shall split this proof into three steps.

First Step. Let $T_* \in (0, T]$ be arbitrarily chosen and let us set

$$M_{T_*} := \{\varpi \in L^2(0, T_*; \mathbf{H}) : \|\varpi\|_{L^2(0, T_*; \mathbf{H})} \leq 1\}.$$

Observing that by the property (2.5), the diffusion term is monotonous as well the damping term, we can use the theory of monotone operators (cf. [17, Section 2.1] together with [9, Section 9]) to prove that for each $\varpi \in M_{T_*}$, there exists a weak solution $v \in L^\infty(0, T_*; \mathbf{H}) \cap L^q(0, T_*; \mathbf{V}_q) \cap \mathbf{L}^\sigma(Q_{T_*})$ to the following system:

$$(3.20) \quad \operatorname{div} v = 0 \quad \text{in } Q_{T_*},$$

$$(3.21) \quad \frac{\partial v}{\partial t} - \operatorname{div} (|\nabla v|^{q-2} \nabla v) + \alpha |v|^{\sigma-2} v = \mathbf{f} - \nabla p - \operatorname{div} (\varpi \otimes \varpi \Phi_\epsilon(|\varpi|)) \quad \text{in } Q_{T_*},$$

$$(3.22) \quad v = \mathbf{u}_0 \quad \text{in } \Omega \quad \text{for } t = 0,$$

$$(3.23) \quad v = \mathbf{0} \quad \text{on } \Gamma_{T_*}.$$

Moreover, once the diffusion and damping terms satisfy the monotonicity property (2.5), the weak solution of (3.20)-(3.23) is unique.

Second Step. As a consequence of the previous step, we can define a mapping

$$(3.24) \quad \mathbf{K} : M_{T_*} \rightarrow L^2(0, T_*; \mathbf{H})$$

such that to each $\varpi \in M_{T_*}$ associates the unique weak solution $v \in L^\infty(0, T_*; \mathbf{H}) \cap L^q(0, T_*; \mathbf{V}_q) \cap \mathbf{L}^\sigma(Q_{T_*})$. Testing formally (3.21) by the unique weak solution $v := \mathbf{K}(\varpi)$, with $\varpi \in M_{T_*}$, integrating over Q_t , with $0 < t < T_*$, using Young's inequality and, at last, the definition of $\Phi_\epsilon(|\varpi|)$, we achieve to

$$(3.25) \quad \begin{aligned} \|v\|_{L^\infty(0, T_*; \mathbf{H})}^2 + C_1 \int_{Q_{T_*}} |\nabla v|^q d\mathbf{x} dt + C_2 \int_{Q_{T_*}} |v|^\sigma d\mathbf{x} dt \leq \\ \gamma_1 + \gamma_2 \|\varpi\|_{L^2(0, T_*; \mathbf{H})}^2, \quad \gamma_1 := \|\mathbf{u}_0\|_{\mathbf{H}}^2 + C_3 \int_{Q_{T_*}} |\mathbf{F}|^{q'} d\mathbf{x} ds, \quad \gamma_2 := C_4. \end{aligned}$$

Then setting $T_* := \min \{1/(\gamma_1 + \gamma_2), T\}$, we can prove, from (3.25) and due to the fact that $\varpi \in M_{T_*}$, that

$$(3.26) \quad \|\mathbf{K}(\varpi)\|_{L^2(0, T_*; \mathbf{H})}^2 \leq T_*(\gamma_1 + \gamma_2) \leq 1$$

for all $\varpi \in M_{T_*}$. This proves that \mathbf{K} maps M_{T_*} into itself.

On the other hand, in order to prove the compactness of \mathbf{K} , we obtain from (3.25) that

$$(3.27) \quad \|\mathbf{K}(\varpi)\|_{L^q(0, T_*; \mathbf{V}_q)} \leq C_1^{-1}(\gamma_1 + \gamma_2)$$

for all $\varpi \in M_{T_*}$. Owing to the assumptions (2.10) and (2.12), the right hand side of (3.27) is finite. Then, for the distributive time derivative $v' := (\mathbf{K}(\varpi))'$, with $\varpi \in M_{T_*}$, we can prove that

$$\|\operatorname{div}(|\nabla v|^{q-2} \nabla v - \varpi \otimes \varpi \Phi_\epsilon(|\varpi|) - \mathbf{F})\|_{L^{q'}(0, T_*; \mathbf{V}'_q)} + \||v|^{\sigma-2} v\|_{\mathbf{L}^{\sigma'}(Q_{T_*})} < \infty$$

and consequently

$$(3.28) \quad v' \in L^{q'}(0, T_*; \mathbf{V}'_q) + \mathbf{L}^{\sigma'}(Q_{T_*}).$$

In fact, by virtue of (3.25), it follows the uniform boundedness of $|\nabla v|^{q-2} \nabla v$ in $\mathbf{L}^{q'}(Q_{T_*})$ and of $|v|^{\sigma-2} v$ in $\mathbf{L}^{\sigma'}(Q_{T_*})$. By assumption (2.12), $\mathbf{F} \in \mathbf{L}^{q'}(Q_{T_*})$. On the other hand, using the definition of Φ_ϵ , we can prove that $\|\varpi \otimes \varpi \Phi_\epsilon(|\varpi|)\|_{\mathbf{L}^{q'}(Q_{T_*})}^{q'} \leq C \|\varpi\|_{L^2(0, T_*; \mathbf{H})}^2$. By (3.27) and (3.28), and once that $\mathbf{V}_q \subset \subset \mathbf{H} \subset \mathbf{V}'_q$ for $q > \frac{2N}{N+2}$, we can apply Aubin-Lions compactness lemma (cf. [21]) to prove that $\mathbf{K}(M_{T_*})$ is relatively compact in $L^q(0, T_*; \mathbf{H})$. Then, since $v \in L^\infty(0, T_*; \mathbf{H})$, by parabolic interpolation it follows that $\mathbf{K}(M_{T_*})$ is relatively compact in $L^2(0, T_*; \mathbf{H})$.

To prove the continuity of \mathbf{K} , we consider a sequence ϖ_m in M_{T_*} such that

$$\varpi_m \rightarrow \varpi \quad \text{in } L^2(0, T_*; \mathbf{H}) \quad \text{as } m \rightarrow \infty.$$

By the relative compactness of $\mathbf{K}(M_{T_*})$ in $L^2(0, T_*; \mathbf{H})$, there exists a subsequence ϖ_{m_k} such that

$$(3.29) \quad \mathbf{K}(\varpi_{m_k}) \rightarrow v \quad \text{in } L^2(0, T_*; \mathbf{H}), \quad \text{as } k \rightarrow \infty.$$

From the definition of \mathbf{K} , the functions $v_{m_k} := \mathbf{K}(\varpi_{m_k})$ satisfy to

$$(3.30) \quad \begin{aligned} & - \int_{Q_{T_*}} v_{m_k} \cdot \varphi_t d\mathbf{x} dt + \int_{Q_{T_*}} |\nabla v_{m_k}|^{q-2} \nabla v_{m_k} : \nabla \varphi d\mathbf{x} dt \\ & + \alpha \int_{Q_{T_*}} |v_{m_k}|^{\sigma-2} v_{m_k} \cdot \varphi d\mathbf{x} dt \\ & = \int_{Q_{T_*}} (\mathbf{F} + \varpi_{m_k} \otimes \varpi_{m_k} \Phi_\epsilon(|\varpi_{m_k}|)) : \nabla \varphi d\mathbf{x} dt + \int_{\Omega} \mathbf{u}_0 \cdot \varphi(0) d\mathbf{x} \end{aligned}$$

for all $\varphi \in \mathbf{C}^\infty(Q_{T_*})$, with $\operatorname{div} \varphi = 0$ and $\operatorname{supp} \varphi \subset\subset \Omega \times [0, T_*]$. Passing to the limit in (3.30) by using the appropriated convergence results (see [24, p. 119] and [9, p. 236]) and the usual Minty trick (see *e.g.* [17, pp. 212-214]), we can prove that $v = \mathbf{K}(\varpi)$. The only difference here is that $|v_{m_k}|^{\sigma-2}v_{m_k} \rightarrow \tilde{v}$ weakly in $\mathbf{L}^\sigma(Q_{T_*})$, as $k \rightarrow \infty$. Since $v_{m_k} \rightarrow v$ weakly in $\mathbf{L}^\sigma(Q_{T_*})$, as $k \rightarrow \infty$, there exists a subsequence, still denoted by v_{m_k} , such that $v_{m_k} \rightarrow v$ a.e. in Q_{T_*} . In addition, because $|v_{m_k}|^{\sigma-2}v_{m_k}$ is uniformly bounded in $\mathbf{L}^\sigma(Q_{T_*})$, we can apply Lesbesgue's theorem of dominated convergence to prove that

$$(3.31) \quad |v_{m_k}|^{\sigma-2}v_{m_k} \rightarrow |v|^{\sigma-2}v \quad \text{strongly in } \mathbf{L}^\sigma(Q_{T_*})$$

and, as a consequence, $\tilde{v} = |v|^{\sigma-2}v$. From (3.29), we conclude that $\mathbf{K}(\varpi_m) \rightarrow \mathbf{K}(\varpi)$ in $\mathbf{L}^2(0, T_*; \mathbf{H})$ as $m \rightarrow \infty$, which proves the continuity of \mathbf{K} .

Now, applying Schauder's fixed point theorem, there exists a function $v_{T_*} \in M_{T_*}$ such that $\mathbf{K}(v_{T_*}) = v_{T_*}$ and which is a weak solution to the problem (3.14)-(3.17) in the cylinder Q_{T_*} .

Third Step. Testing (3.15) by the weak solution v_{T_*} , integrating over Q_{T_*} , proceeding we did as for (3.25) and observing that due to the definition of Φ_ϵ the term resulting from convection is zero, we obtain

$$(3.32) \quad \|v_{T_*}(T_*)\|_{\mathbf{H}}^2 \leq C \left(\|\mathbf{u}_0\|_{\mathbf{H}}^2 + \|\mathbf{F}\|_{\mathbf{L}^{q'}(Q_{T_*})}^{q'} \right).$$

The estimate (3.32) is independent of T_* and therefore we can extend v_{T_*} as a weak solution to the problem (3.14)-(3.17) in the whole cylinder Q_T .

Finally, the energy relation (3.19) follows by testing (3.15) by a weak solution and integrating over Q_t with $0 < t < T_*$. \square

4. EXISTENCE OF APPROXIMATE SOLUTIONS

Let $\mathbf{u}_\epsilon \in \mathbf{L}^q(0, T; \mathbf{V}_q) \cap \mathbf{L}^\infty(0, T; \mathbf{H}) \cap \mathbf{L}^\sigma(Q_T)$ be a weak solution to the problem (3.14)-(3.17). From Proposition 3.1 (see (3.19)), we can prove that

$$(4.33) \quad \|\mathbf{u}_\epsilon\|_{\mathbf{L}^\infty(0, T; \mathbf{H})}^2 + \int_{Q_T} |\nabla \mathbf{u}_\epsilon|^q d\mathbf{x} dt + \int_{Q_T} |\mathbf{u}_\epsilon|^\sigma d\mathbf{x} dt \leq C,$$

where, by the assumptions (2.10) and (2.12), C is a positive constant which does not depend on ϵ . From (4.33) we obtain

$$(4.34) \quad \|\mathbf{u}_\epsilon\|_{\mathbf{L}^\infty(0, T; \mathbf{H})}^2 + \|\mathbf{u}_\epsilon\|_{\mathbf{L}^q(0, T; \mathbf{V}_q)}^q \leq C,$$

$$(4.35) \quad \|\mathbf{u}_\epsilon\|_{\mathbf{L}^\sigma(Q_T)} \leq C.$$

Using (4.34) and (4.35), it follows that

$$(4.36) \quad \||\nabla \mathbf{u}_\epsilon|^{q-2} \nabla \mathbf{u}_\epsilon\|_{\mathbf{L}^{q'}(Q_T)} \leq C,$$

$$(4.37) \quad \||\mathbf{u}_\epsilon|^{\sigma-2} \mathbf{u}_\epsilon\|_{\mathbf{L}^{\sigma'}(Q_T)} \leq C.$$

On the other hand, by using (4.34) and the Sobolev imbedding $\mathbf{L}^q(0, T; \mathbf{V}_q) \cap \mathbf{L}^\infty(0, T; \mathbf{H}) \hookrightarrow \mathbf{L}^{q \frac{N+2}{N}}(Q_T)$ (see [17, p. 213]), we can prove that

$$(4.38) \quad \|\mathbf{u}_\epsilon\|_{\mathbf{L}^{q \frac{N+2}{N}}(Q_T)} \leq C.$$

As a consequence of (4.38) and of the definition of Φ_ϵ (see (3.13)),

$$(4.39) \quad \|\mathbf{u}_\epsilon \otimes \mathbf{u}_\epsilon \Phi_\epsilon(|\mathbf{u}_\epsilon|)\|_{\mathbf{L}^{q \frac{N+2}{2N}}(Q_T)} \leq C.$$

Note that the constants in (4.34)-(4.39) are distinct and do not depend on ϵ . From (4.34)-(4.39), there exists a sequence of positive numbers ϵ_m such that $\epsilon_m \rightarrow 0$, as $m \rightarrow \infty$, and

$$(4.40) \quad \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{weakly in } L^q(0, T; \mathbf{V}_q), \quad \text{as } m \rightarrow \infty,$$

$$(4.41) \quad \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{weakly in } \mathbf{L}^\sigma(Q_T), \quad \text{as } m \rightarrow \infty,$$

$$(4.42) \quad |\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{S} \quad \text{weakly in } \mathbf{L}^{q'}(Q_T), \quad \text{as } m \rightarrow \infty,$$

$$(4.43) \quad |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} \rightarrow \tilde{\mathbf{u}} \quad \text{weakly in } \mathbf{L}^{\sigma'}(Q_T), \quad \text{as } m \rightarrow \infty,$$

$$(4.44) \quad \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{weakly in } L^{q \frac{N+2}{N}}(0, T; \mathbf{V}_q), \quad \text{as } m \rightarrow \infty,$$

$$(4.45) \quad \mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) \rightarrow \mathbf{G} \quad \text{weakly in } \mathbf{L}^{q \frac{N+2}{2N}}(Q_T), \quad \text{as } m \rightarrow \infty.$$

Here we observe that using (4.43) and arguing as in the proof of Proposition 3.1 (see (3.31)), we can prove that

$$(4.46) \quad |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} \rightarrow |\mathbf{u}|^{\sigma-2} \mathbf{u} \quad \text{strongly in } \mathbf{L}^{\sigma'}(Q_T).$$

As a consequence, we can write $\tilde{\mathbf{u}} = |\mathbf{u}|^{\sigma-2} \mathbf{u}$. Then, using the convergence results (4.40)-(4.46), we can pass to the limit $\epsilon_m \rightarrow 0$ in (3.18) with \mathbf{u}_ϵ replaced by \mathbf{u}_{ϵ_m} , to obtain

$$(4.47)$$

$$-\int_{Q_T} \mathbf{u} \cdot \varphi_t \, d\mathbf{x} dt + \alpha \int_{Q_T} |\mathbf{u}|^{\sigma-2} \mathbf{u} \cdot \varphi \, d\mathbf{x} dt + \int_{Q_T} (\mathbf{S} - \mathbf{G} - \mathbf{F}) : \nabla \varphi \, d\mathbf{x} dt = \int_{\Omega} \mathbf{u}_0 \cdot \varphi(0) \, d\mathbf{x}$$

for all $\varphi \in \mathbf{C}^\infty(Q_T)$, with $\operatorname{div} \varphi = 0$ and $\operatorname{supp} \varphi \subset \subset \Omega \times [0, T]$.

5. CONVERGENCE OF THE APPROXIMATED CONVECTIVE TERM

In this section we shall prove that $\mathbf{G} = \mathbf{u} \otimes \mathbf{u}$. We start by observing that, from (3.18), it follows

$$(5.48) \quad \begin{aligned} & - \int_{Q_T} \mathbf{u}_{\epsilon_m} \cdot \varphi_t \, d\mathbf{x} dt + \alpha \int_{Q_T} |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} \cdot \varphi \, d\mathbf{x} dt + \\ & \int_{Q_T} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{F}) : \nabla \varphi \, d\mathbf{x} dt = 0 \end{aligned}$$

for all $\varphi \in \mathbf{C}_0^\infty(Q_T)$ with $\operatorname{div} \varphi = 0$. Then, from (2.12), (4.36) and (4.39), we have

$$(5.49) \quad \mathbf{Q}_{\epsilon_m} := |\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{F} \in \mathbf{L}^r(Q_T)$$

for any r satisfying to

$$(5.50) \quad 1 < r \leq \min \left\{ \frac{q(N+2)}{2N}, q' \right\}.$$

Using (4.37) and (5.49)-(5.50), we can obtain, from (5.48), that the distributive time derivatives

$$(5.51) \quad \mathbf{u}'_{\epsilon_m} \in L^r(0, T; \mathbf{W}^{-1, r}(\Omega)) + \mathbf{L}^{\sigma'}(Q_T).$$

Due to the admissible range for r (see (5.50)), there always exists a $\gamma > 1$ such that the following compact and Sobolev imbeddings hold

$$(5.52) \quad \mathbf{W}_0^{1, q}(\Omega) \subset \subset \mathbf{L}^\gamma(\Omega) \subset \mathbf{W}^{-1, r}(\Omega), \quad ((r')^*)' \leq \gamma < q^*,$$

where q^* is the Sobolev conjugate of q and r' is the Hölder conjugate of r . Then, using Aubin-Lions compactness lemma (cf. Simon [21]), we obtain from (4.40) together with (5.51) and (5.52), and passing to a subsequence, that

$$(5.53) \quad \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{strongly in } L^r(0, T; \mathbf{L}^\gamma(\Omega)), \quad \text{as } m \rightarrow \infty.$$

Using parabolic interpolation, we obtain from (4.34) and (5.53) that

$$(5.54) \quad \mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{strongly in } L^s(0, T; \mathbf{L}^\gamma(\Omega)) \quad \forall s : 1 \leq s < \infty, \quad \text{as } m \rightarrow \infty.$$

Now, observing that $q > \frac{2N}{N+2}$ is equivalent to $q^* > q \frac{N+2}{N}$, we can choose γ such that $q \frac{N+2}{N} \leq \gamma < q^*$ such that, in view of (5.54),

$$\mathbf{u}_{\epsilon_m} \rightarrow \mathbf{u} \quad \text{strongly in } L^s(Q_T), \quad s = q \frac{N+2}{N}, \quad \text{as } m \rightarrow \infty.$$

In consequence

$$(5.55) \quad \mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) \rightarrow \mathbf{u} \otimes \mathbf{u} \quad \text{strongly in } \mathbf{L}^{q \frac{N+2}{2N}}(Q_T), \quad \text{as } m \rightarrow \infty.$$

Finally, from (4.45) and (5.55), we conclude that $\mathbf{G} = \mathbf{u} \otimes \mathbf{u}$.

6. WEAK CONTINUITY

We start this section by proving that

$$(6.56) \quad \mathbf{u} \in C_w([0, T]; \mathbf{H}).$$

We observe that, from (4.47), the distributive time derivative \mathbf{u}_t is uniquely defined by

$$(6.57) \quad \langle \mathbf{u}_t, \varphi \rangle = \langle \mathbf{div}(\mathbf{S} - \mathbf{G}) - \alpha |\mathbf{u}|^{\sigma-2} \mathbf{u} + \mathbf{F}, \varphi \rangle \quad \forall \varphi \in C_0^\infty(0, T; \mathbf{Y}),$$

where

$$(6.58) \quad \mathbf{Y} := \mathbf{V}_q \cap \mathbf{V}_\kappa \cap \mathbf{L}^\sigma(Q_T) \cap \mathbf{H}, \quad \kappa := \left(\frac{q(N+2)}{2N} \right)'.$$

Then we can prove that

$$(6.59) \quad \mathbf{u}_t \in L^{\frac{N+1}{N}}(0, T; \mathbf{Y}').$$

In fact, due to (4.42) and (4.43), immediately follows that $\mathbf{div} \mathbf{S} \in L^{\frac{N+1}{N}}(0, T; \mathbf{V}'_q)$ and $|\mathbf{u}|^{\sigma-2} \mathbf{u} \in \mathbf{L}^{\sigma'}(Q_T)$, respectively. By assumption (2.12), $\mathbf{F} \in L^{\frac{N+1}{N}}(0, T; \mathbf{V}'_q)$. That $\mathbf{div} \mathbf{G} \in L^{\frac{N+1}{N}}(0, T; \mathbf{V}'_\kappa)$ follows by (4.45) if $k' = q \frac{N+2}{2N}$, which in fact is true by our choice of k (cf. (6.58)).

Next, let $t_0 \in [0, T]$ be fixed and let t_k be a sequence in $[0, T]$ such that

$$t_k \rightarrow t_0, \quad \text{as } k \rightarrow \infty, \quad \text{and such that } \mathbf{u}(t_k) \in \mathbf{H} \quad \forall k \in \mathbb{N}.$$

Then we consider the continuous representant of \mathbf{u} in $C(0, T; \mathbf{Y}')$, which exists by virtue of (6.57) and (6.59). Finally by means of reflexivity in \mathbf{H} and of the continuous and dense imbedding of \mathbf{H} into \mathbf{Y}' , we can prove that

$$\mathbf{u}(t_k) \rightarrow \mathbf{u}(t_0) \quad \text{weakly in } \mathbf{H}, \quad \text{as } k \rightarrow \infty,$$

and whence (6.56).

Now, let us prove that for every $t \in [0, T]$

$$(6.60) \quad \mathbf{u}_{\epsilon_m}(t) \rightarrow \mathbf{u}(t) \quad \text{weakly in } \mathbf{H}, \quad \text{as } m \rightarrow \infty.$$

Due to (4.34), there exists a subsequence $\mathbf{u}_{\epsilon_{m_k}}(t) \in \mathbf{H}$ such that

$$\mathbf{u}_{\epsilon_{m_k}}(t) \rightarrow \eta \quad \text{weakly in } \mathbf{H}, \quad \text{as } m \rightarrow \infty.$$

Arguing as we did for (6.57) and (6.59), the distributive time derivative $\mathbf{u}'_{\epsilon_{m_k}} \in L^{\frac{N+1}{N}}(0, T; \mathbf{Y}')$ and is uniquely defined by

$$(6.61) \quad \begin{aligned} \langle \mathbf{u}'_{\epsilon_{m_k}}, \varphi \rangle = \\ \langle \operatorname{div}(|\nabla \mathbf{u}_{\epsilon_{m_k}}|^{q-2} \nabla \mathbf{u}_{\epsilon_{m_k}} - \mathbf{u}_{\epsilon_{m_k}} \otimes \mathbf{u}_{\epsilon_{m_k}} \Phi_{\epsilon_{m_k}}(|\mathbf{u}_{\epsilon_{m_k}}|)) - \alpha |\mathbf{u}_{\epsilon_{m_k}}|^{\sigma-2} \mathbf{u}_{\epsilon_{m_k}} + \mathbf{F}, \varphi \rangle \end{aligned}$$

for all $\varphi \in C_0^\infty(0, T; \mathbf{Y})$. In particular, there holds $\mathbf{u}_{\epsilon_{m_k}} \in C(0, T; \mathbf{Y}')$. Next, we introduce η in (6.61), we use integration by parts and we carry out the passage to the limit in the resulting equation by using the convergence results (4.40)-(4.45). Combining this equation with the one which results from inserting η into (6.57) and integrating by parts, we obtain $\mathbf{u}(t) = \eta$, which yields (6.60). Finally, combining (6.56) and (6.60), we see that also \mathbf{u}_{ϵ_m} satisfies to (6.56).

7. AUXILIARY RESULTS FOR DECOMPOSING THE PRESSURE

Here we make a break in the proof of Theorem 2.1 to show that the results of Wolf [12] concerned with the local decomposition of the pressure still hold in the case of the momentum equation modified by the presence of the damping term. For, let ω' be a fixed but arbitrary open bounded subset of Ω such that

$$(7.62) \quad \omega' \subset \subset \Omega \quad \text{and} \quad \partial \omega' \in C^2.$$

Given s such that $1 < s < \infty$, lets us consider the following auxiliary function spaces related with the Helmholtz-Weyl decomposition (cf. [24, Section 2], see also [15, Section III.1] and [20]):

$$(7.63) \quad A^s(\omega') := \{a \in L^s(\omega') : a = \Delta f, f \in W_0^{2,s}(\omega')\};$$

$$(7.64) \quad \dot{B}^s(\omega') := \left\{ b \in B^s(\omega') : \int_{\omega'} b \, d\mathbf{x} = 0 \right\}, \quad B^s(\omega') := \{b \in L^s(\omega') : \Delta b = 0\}.$$

Proposition 7.1. *Let $\mathbf{Q} \in L^{s_1}(\omega'_T)$, $\mathbf{q} \in L^{s_2}(\omega'_T)$, with $1 < s_1, s_2 < \infty$, and*

$$(7.65) \quad \mathbf{u} \in C_w([0, T]; \mathbf{H})$$

where here \mathbf{H} is defined over ω' . Suppose that

$$(7.66) \quad - \int_{\omega'_T} \mathbf{u} \cdot \varphi_t \, d\mathbf{x} dt + \int_{\omega'_T} \mathbf{Q} : \nabla \varphi \, d\mathbf{x} dt + \int_{\omega'_T} \mathbf{q} \cdot \varphi \, d\mathbf{x} dt = 0$$

for all $\varphi \in C_0^\infty(\omega'_T)$ with $\operatorname{div} \varphi = 0$ and where $\omega'_T = \omega' \times (0, T)$ and ω' satisfies to (7.62). Then there exist unique functions

$$(7.67) \quad p^0 \in L^{s_0}(0, T; A^{s_0}(\omega')),$$

$$(7.68) \quad \tilde{p}^h \in C_w([0, T]; \dot{B}^{s_0}(\omega')),$$

where s_0 can be taken such that

$$(7.69) \quad 1 < s_0 \leq \min \{s_1, s_2\},$$

such that

$$(7.70) \quad \begin{aligned} & - \int_{\omega'_T} \mathbf{u} \cdot \varphi_t \, d\mathbf{x} dt + \int_{\omega'_T} \mathbf{Q} : \nabla \varphi \, d\mathbf{x} dt + \int_{\omega'_T} \mathbf{q} \cdot \varphi \, d\mathbf{x} dt \\ & = \int_{\omega'_T} p^0 \operatorname{div} \varphi \, d\mathbf{x} dt - \int_{\omega'_T} \tilde{p}^h \frac{\partial \operatorname{div} \varphi}{\partial t} \, d\mathbf{x} dt + \int_{\omega'} \mathbf{u}(0) \cdot \varphi(0) \, dt \end{aligned}$$

for all $\varphi \in \mathbf{C}^\infty(\omega'_T)$, with $\operatorname{supp} \varphi \subset \subset \omega' \times [0, T)$. In addition, the following estimates hold

$$(7.71) \quad \|p^0\|_{\mathbf{L}^{s_0}(\omega'_T)} \leq C_1 \left(\|\mathbf{Q}\|_{\mathbf{L}^{s_1}(\omega'_T)} + \|\mathbf{q}\|_{\mathbf{L}^{s_2}(\omega'_T)} \right),$$

$$(7.72) \quad \|\tilde{p}^h\|_{\mathbf{L}^\infty(0, T; \mathbf{L}^{s_0}(\omega'))} \leq C_2 \left(\|\mathbf{u}\|_{\mathbf{L}^\infty(0, T; \mathbf{L}^2(\omega'))} + \|\mathbf{Q}\|_{\mathbf{L}^{s_1}(\omega'_T)} + \|\mathbf{q}\|_{\mathbf{L}^{s_2}(\omega'_T)} \right).$$

where C_1 and C_2 are positive constants depending only on s_i ($i = 0, 1, 2$), N and ω'_T .

Proof. Let $\psi \in \mathbf{C}_0^\infty(\omega')$ with $\operatorname{div} \psi = 0$ and let $\eta \in \mathbf{C}_0^\infty(0, T)$. Inserting $\varphi = \psi \eta$ into (7.66) and using Fubini's theorem, we obtain

$$- \int_0^T \alpha \eta' \, dt = \int_0^T \beta \eta \, dt + \int_0^T \gamma \eta \, dt,$$

where for $t \in [0, T]$

$$\alpha(t) := \int_{\omega'} \mathbf{u}(t) \cdot \psi \, d\mathbf{x}, \quad \beta(t) := \int_{\omega'} \mathbf{Q}(t) : \nabla \psi \, d\mathbf{x}, \quad \gamma(t) := \int_{\omega'} \mathbf{q}(t) \cdot \psi \, d\mathbf{x}.$$

Since $\mathbf{Q} \in \mathbf{L}^{s_1}(\omega'_T)$ and $\mathbf{q} \in \mathbf{L}^{s_2}(\omega'_T)$, we have $\beta \in \mathbf{L}^{s_1}(0, T)$ and $\gamma \in \mathbf{L}^{s_2}(0, T)$. In consequence, $\alpha \in \mathbf{W}^{1, s_0}(\omega'_T)$ for any s_0 such that $1 < s_0 \leq \min\{s_1, s_2\}$. By Sobolev's imbedding theorem, α is represented by a continuous function, which we still denote by α . Using integration by parts, we can represent

$$(7.73) \quad \alpha(t) = \alpha(0) + \int_0^t \beta(s) \, ds + \int_0^t \gamma(s) \, ds \quad \forall t \in (0, T).$$

Let $t \in (0, T)$ be arbitrarily chosen. Using Fubini's theorem, the identity (7.73) reads

$$\int_{\omega'} \left[(\mathbf{u}(t) - \mathbf{u}(0)) \cdot \psi + \tilde{\mathbf{q}}(t) \cdot \psi + \tilde{\mathbf{Q}}(t) : \nabla \psi \right] d\mathbf{x} = 0,$$

where

$$\tilde{\mathbf{Q}}(t) := \int_0^t \mathbf{Q}(s) \, ds, \quad \tilde{\mathbf{q}}(t) := \int_0^t \mathbf{q}(s) \, ds.$$

Now, by the results of M.E. Bogovskiĭ (cf. [15, Theorem III.3.1]) and of K.I. Piletskas (cf. [15, Theorem III.5.2]), there exists a unique function

$$\tilde{p}(t) \in \mathbf{L}^{s_0}(\omega') \quad \text{with} \quad \int_{\omega'} \tilde{p}(t) \, d\mathbf{x} = 0$$

such that

$$(7.74) \quad \int_{\omega'} \left[(\mathbf{u}(t) - \mathbf{u}(0)) \cdot \psi + \tilde{\mathbf{q}}(t) \cdot \psi + \tilde{\mathbf{Q}}(t) : \nabla \psi \right] d\mathbf{x} = \int_{\omega'} \tilde{p}(t) \operatorname{div} \psi \, d\mathbf{x}$$

for all $\psi \in \mathbf{W}_0^{1, s_0}(\omega')$. In addition,

$$(7.75) \quad \|\tilde{p}^h(t)\|_{\mathbf{L}^{s_0}(\omega')} \leq C \left(\|\mathbf{u}(t) - \mathbf{u}(0)\|_{\mathbf{L}^{s_0}(\omega')} + \|\tilde{\mathbf{Q}}(t)\|_{\mathbf{L}^{s_0}(\omega')} + \|\tilde{\mathbf{q}}(t)\|_{\mathbf{L}^{s_0}(\omega')} \right).$$

On the other hand, by the application of Helmholtz-Weyl decomposition of $\mathbf{L}^{s_0}(\omega')$ (cf. [20, Theorem 1.4]), there exist $\tilde{p}^0(t) \in A^{s_0}(\omega')$ and $\tilde{p}^h(t) \in \dot{B}^{s_0}(\omega')$ such that

$$(7.76) \quad \tilde{p}(t) = \tilde{p}^0(t) + \tilde{p}^h(t) \quad \text{in } \omega'$$

and where $A^r(\omega')$ and $\dot{B}^r(\omega')$ are defined in (7.63)-(7.64). Moreover, the sum $A^{s_0}(\omega') + \dot{B}^{s_0}(\omega')$ is direct. Now, from (7.74) and, as a consequence of the assumption (7.65), we can infer that

$$(7.77) \quad \tilde{p} \in C_w([0, T]; L^{s_0}(\omega')).$$

From (7.76) and (7.77) it follows that

$$(7.78) \quad \tilde{p}^0 \in C_w([0, T]; A^{s_0}(\omega')).$$

$$(7.79) \quad \tilde{p}^h \in C_w([0, T]; \dot{B}^{s_0}(\omega')).$$

As a consequence of (7.75), (7.76), we can derive (7.72). Moreover, inserting $\psi = \nabla\phi$ in (7.74), for $\phi \in C_0^\infty(\omega')$, using (7.76), integrating by parts the resulting equation and observing that, in view of (7.79), $\Delta\tilde{p}^h = 0$, and, in view of (7.65), $\operatorname{div}\mathbf{u} = 0$, we obtain

$$(7.80) \quad \int_{\omega'} \left(\tilde{\mathbf{q}}(t) \cdot \nabla\phi + \tilde{\mathbf{Q}}(t) : \nabla^2\phi \right) d\mathbf{x} = \int_{\omega'} \tilde{p}^0(t) \Delta\phi d\mathbf{x}$$

for all $\phi \in C_0^\infty(\omega')$. Now, using (7.80) and proceeding as in [24, pp. 115-116], we can prove that $\tilde{p}^0 \in W^{1,s_0}(0, T; A^{s_0}(\omega'))$ and

$$(7.81) \quad \|p^0\|_{\mathbf{L}^{s_0}(\omega'_T)} \leq C \left(\|\mathbf{Q}\|_{\mathbf{L}^{s_1}(\omega'_T)} + \|\mathbf{q}\|_{\mathbf{L}^{s_2}(\omega'_T)} \right), \quad \text{where } p^0 := \frac{\partial \tilde{p}^0}{\partial t}$$

and the constant C depends only on s_i ($i = 1, 2, 3$), N and ω'_T . Whence (7.71) holds. Finally, the identity (7.70) follows by integrating (7.74) over $(0, T)$, replacing there φ by $\frac{\partial \varphi}{\partial t}$ and using (7.76), (7.78), (7.79) and the definition of p^0 given in (7.81). The uniqueness of p^0 and \tilde{p}^h follow from (7.71) and (7.72), respectively. \square

8. DECOMPOSITION OF THE PRESSURE.

Let us continue with the proof of Theorem 2.1. Using the results of the previous section, we shall decompose the pressure into two different components. For, let ω' be a domain in the conditions of the previous section (see (7.62)). Clearly, in view of (5.48) and with the notation introduced in (5.49), we can write

$$(8.82) \quad - \int_{\omega'_T} \mathbf{u}_{\epsilon_m} \cdot \varphi_t d\mathbf{x} dt + \alpha \int_{\omega'_T} |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} \cdot \varphi d\mathbf{x} dt + \int_{\omega'_T} \mathbf{Q}_{\epsilon_m} : \nabla\varphi d\mathbf{x} dt = 0$$

for all $\varphi \in \mathbf{C}_0^\infty(\omega'_T)$ with $\operatorname{div}\varphi = 0$ and where $\omega'_T := \omega' \times (0, T)$. The results (8.82) and (6.56) allow us to apply Proposition 7.1 with $\mathbf{Q} = \mathbf{Q}_{\epsilon_m}$, $\mathbf{q} = \alpha|\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m}$, $s_1 = r$, $s_2 = \sigma'$ and

$$(8.83) \quad s_0 = r_0 := \min\{r, \sigma'\}.$$

Observe that by (5.50), $r \leq 2$ and consequently $r_0 \leq 2$. Therefore we can say that exist unique functions

$$(8.84) \quad p_{\epsilon_m}^0 \in L^{r_0}(0, T; A^{r_0}(\omega')),$$

$$(8.85) \quad \tilde{p}_{\epsilon_m}^h \in C_w([0, T]; \dot{B}^{r_0}(\omega')),$$

such that

$$(8.86) \quad \begin{aligned} & - \int_{\omega'_T} \mathbf{u}_{\epsilon_m} \cdot \varphi_t \, d\mathbf{x} dt + \alpha \int_{\omega'_T} |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} \cdot \varphi \, d\mathbf{x} dt + \int_{\omega'_T} \mathbf{Q}_{\epsilon_m} : \nabla \varphi \, d\mathbf{x} dt = \\ & \int_{\omega'_T} p_{\epsilon_m}^0 \operatorname{div} \varphi \, d\mathbf{x} dt - \int_{\omega'_T} \tilde{p}_{\epsilon_m}^h \frac{\partial \operatorname{div} \varphi}{\partial t} \, d\mathbf{x} dt + \int_{\omega'} \mathbf{u}_0 \cdot \varphi(0) \, dt \end{aligned}$$

for all $\varphi \in \mathbf{C}^\infty(\omega'_T)$, with $\operatorname{supp} \varphi \subset \subset \omega' \times [0, T]$. In addition, by the same result, the following estimates hold

$$(8.87) \quad \|p_{\epsilon_m}^0\|_{\mathbf{L}^{r_0}(\omega'_T)} \leq C_1 \left(\|\mathbf{Q}_{\epsilon_m}\|_{\mathbf{L}^r(\omega'_T)} + \|\mathbf{u}_{\epsilon_m}\|_{\mathbf{L}^{\sigma'}(\omega'_T)} \right),$$

$$(8.88) \quad \|\tilde{p}_{\epsilon_m}^h\|_{\mathbf{L}^\infty(0, T; \mathbf{L}^{r_0}(\omega'))} \leq C_2 \left(\|\mathbf{u}_{\epsilon_m}\|_{\mathbf{L}^\infty(0, T; \mathbf{H})} + \|\mathbf{Q}_{\epsilon_m}\|_{\mathbf{L}^r(\omega'_T)} + \|\mathbf{u}_{\epsilon_m}\|_{\mathbf{L}^{\sigma'}(\omega'_T)} \right),$$

where C_1 and C_2 are positive constants depending only on q , σ' , N and ω'_T . Then, from (8.84) and (8.85) and by means of reflexivity, we get, passing to a subsequence if needed, that

$$(8.89) \quad p_{\epsilon_m}^0 \rightarrow \underline{p}^0 \quad \text{in } \mathbf{L}^r(0, T; \mathbf{A}^{r_0}(\omega')), \quad \text{as } m \rightarrow \infty,$$

$$(8.90) \quad \tilde{p}_{\epsilon_m}^h \rightarrow \tilde{p}^h \quad \text{in } \mathbf{L}^{N+1}(0, T; \dot{\mathbf{B}}^{r_0}(\omega')), \quad \text{as } m \rightarrow \infty.$$

Now we pass to the limit $m \rightarrow \infty$ in (8.86) by using the convergence results (4.40), (4.42), (4.43) and (4.45), together with the identities $\tilde{\mathbf{u}} = |\mathbf{u}|^{\sigma-2} \mathbf{u}$ and $\mathbf{G} = \mathbf{u} \otimes \mathbf{u}$, and also the convergence results (8.89) and (8.90). Then we compare this limit equation with that one resulting from applying (8.86) to the limit equation (4.47), considered for all $\varphi \in \mathbf{C}_0^\infty(\omega'_T)$, with $\operatorname{div} \varphi = 0$, and with the aforementioned identities. This procedure yields the existence of unique functions p^0 and \tilde{p}^h satisfying to (8.84)-(8.88). Then, since p^0 and \tilde{p}^h are uniquely defined, we see that

$$\underline{p}^0 = p^0 \quad \text{and} \quad \tilde{p}^h = \tilde{p}^h.$$

Proceeding as in [24, p. 126], letting a be such that $1 < a < \infty$, using the well-known local regularity theory, the compact imbedding $\mathbf{W}^{3,a}(\omega) \hookrightarrow \mathbf{W}^{2,a}(\omega)$ and Lebesgue's theorem of dominated convergence, we can prove that

$$(8.91) \quad \tilde{p}_{\epsilon_m}^h \rightarrow \tilde{p}^h \quad \text{strongly in } \mathbf{L}^a(0, T; \mathbf{W}^{2,a}(\omega)), \quad \text{as } m \rightarrow \infty,$$

where ω is a fixed but arbitrary open bounded subset of Ω such that

$$(8.92) \quad \omega \subset \subset \omega' \subset \subset \Omega, \quad \text{with } \partial\omega \text{ Lipschitz.}$$

Let us set now

$$(8.93) \quad \mathbf{v}_{\epsilon_m} := \mathbf{u}_{\epsilon_m} + \nabla \tilde{p}_{\epsilon_m}^h,$$

$$(8.94) \quad \mathbf{v} := \mathbf{u} + \nabla \tilde{p}^h.$$

Then, combining (8.86) with this same equation when we pass it to the limit $m \rightarrow \infty$, and using the definition of the distributive time derivative, we obtain

$$(8.95) \quad \begin{aligned} (\mathbf{v}_{\epsilon_m} - \mathbf{v})' &= \operatorname{div} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) - \alpha (|\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2} \mathbf{u}) \quad \text{in } \mathcal{D}'(\omega'_T) \\ &\quad - \operatorname{div} (\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}) - \nabla (p_{\epsilon_m}^0 - p^0) \end{aligned}$$

Proceeding as for (5.51), attending to (8.89) and observing that $r_0 \leq r$, we can prove that

$$(\mathbf{v}_{\epsilon_m} - \mathbf{v})' \in L^{r_0}(0, T; \mathbf{W}^{-1, r_0}(\omega')) + \mathbf{L}^{\sigma'}(\omega'_T).$$

Now we shall decompose the pressure term $(p_{\epsilon_m}^0 - p^0)$ in (8.95) into three new functions. For that, we need to invoke the following results, whose proofs follow immediately from [24, Lemmas 2.3 and 2.4].

Lemma 8.1. *Let $1 < s < \infty$ and $k \in \mathbb{N}$.*

(1) *Then for every $v^* \in \left(W_0^{k, s'}(\omega)\right)'$ there exists a unique $v \in W_0^{k, s}(U)$ such that*

$$\int_{\omega} D^{\alpha} v D^{\alpha} \varphi d\mathbf{x} = \langle v^*, \varphi \rangle \quad \forall \varphi \in C_0^{\infty}(\omega), \quad |\alpha| = k.$$

(2) *In addition, if exists $\mathcal{H} \in L^s(\omega)$ such that*

$$\langle v^*, \varphi \rangle = \int_{\omega} \mathcal{H} D^{\alpha} \varphi d\mathbf{x} \quad \forall \varphi \in C_0^{\infty}(\omega), \quad |\alpha| = k,$$

then

$$\|D^{\alpha} v\|_{L^s(\omega)} \leq C \|\mathcal{H}\|_{L^s(\omega)},$$

where C is a positive constant depending on s and on the Calderón-Zigmund inequality's constant.

By a direct application of the first part of Lemma 8.1, attending to (4.42), (4.43) and (4.45), and to the definitions of $A^{q'}(\omega')$ and $A^{q \frac{N+2}{2N}}(\omega')$, there exist unique functions

$$(8.96) \quad p_{\epsilon_m}^1 \in L^{q'}(0, T; A^{q'}(\omega')),$$

$$(8.97) \quad p_{\epsilon_m}^2 \in L^{q \frac{N+2}{2N}}(0, T; A^{q \frac{N+2}{2N}}(\omega')),$$

$$(8.98) \quad p_{\epsilon_m}^3 \in L^{\sigma'}(0, T; W_0^{1, \sigma'}(\omega')),$$

such that

$$(8.99) \quad \int_{\omega'_T} p_{\epsilon_m}^1 \Delta \phi d\mathbf{x} dt = \int_{\omega'_T} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla^2 \phi d\mathbf{x} dt,$$

$$(8.100) \quad \int_{\omega'_T} p_{\epsilon_m}^2 \Delta \phi d\mathbf{x} dt = - \int_{\omega'_T} (\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}) : \nabla^2 \phi d\mathbf{x} dt,$$

$$(8.101) \quad \int_{\omega'_T} p_{\epsilon_m}^3 \Delta \phi d\mathbf{x} dt = \alpha \int_{\omega'_T} (|\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2} \mathbf{u}) \cdot \nabla \phi d\mathbf{x} dt$$

for all $\phi \in C_0^{\infty}(\omega'_T)$. In addition, by (8.99)-(8.101) and a direct application of the second part of Lemma 8.1, the following estimates hold:

$$(8.102) \quad \|p_{\epsilon_m}^1\|_{L^{q'}(\omega'_T)} \leq C_1 \||\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}\|_{L^{q'}(\omega'_T)};$$

$$(8.103) \quad \|p_{\epsilon_m}^2\|_{L^{q \frac{N+2}{2N}}(\omega'_T)} \leq C_2 \|\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}\|_{L^{q \frac{N+2}{2N}}(\omega'_T)};$$

$$(8.104) \quad \|\nabla p_{\epsilon_m}^3\|_{L^{\sigma'}(\omega'_T)} \leq C_3 \||\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2} \mathbf{u}\|_{L^{\sigma'}(\omega'_T)};$$

where C_1, C_2 and C_3 are positive constants depending on $q', q \frac{N+2}{2N}$ and σ' , respectively, and on the Calderón-Zigmund inequality's constant (C_3 depends also on α). Next, testing (8.95) by $\nabla\phi$, with $\phi \in C_0^\infty(\omega_T)$, integrating over ω_T and using (3.14) and (7.68) together with (7.64), and also the identities (8.99)-(8.101), we obtain

$$p_{\epsilon_m}^0 - p^0 = p_{\epsilon_m}^1 + p_{\epsilon_m}^2 + p_{\epsilon_m}^3.$$

Inserting this into (8.95), it follows that

$$\begin{aligned} (8.105) \quad (\mathbf{v}_{\epsilon_m} - \mathbf{v})' &= \operatorname{div}(|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) - \alpha(|\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2} \mathbf{u}) \\ &\quad - \operatorname{div}(\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}) \\ &\quad - \nabla p_{\epsilon_m}^1 - \nabla p_{\epsilon_m}^2 - \nabla p_{\epsilon_m}^3 \end{aligned} \quad \text{in } \mathcal{D}'(\omega_T).$$

9. DEFINITION OF THE IRREGULARITY REGIONS

Let us consider the following slight modification of the functions (8.93)-(8.94)

$$(9.106) \quad \mathbf{w}_{\epsilon_m} := (\mathbf{v}_{\epsilon_m} - \mathbf{v}) \chi_{\omega_T} \equiv (\mathbf{u}_{\epsilon_m} + \nabla \tilde{p}_{\epsilon_m}^h - (\mathbf{u} + \nabla \tilde{p}^h)) \chi_{\omega_T},$$

where χ_{ω_T} denotes the characteristic function of the set $\omega_T := \omega \times (0, T)$ and ω satisfies to (8.92). Having in mind the extension of (8.105) to \mathbb{R}^{N+1} , here we shall consider that

$$(9.107) \quad \mathbf{Q}_{\epsilon_m}^1 := \mathbf{S} - |\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} + p_{\epsilon_m}^1 \mathbf{I},$$

$$(9.108) \quad \mathbf{Q}_{\epsilon_m}^2 := \mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u} + p_{\epsilon_m}^2 \mathbf{I},$$

$$(9.109) \quad \mathbf{q}_{\epsilon_m} := \alpha(|\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2} \mathbf{u}) + \nabla p_{\epsilon_m}^3,$$

are extended from ω_T to \mathbb{R}^{N+1} by zero. Now, since $q < q^*$, we can use (5.54), with $s = \gamma = q$, together with (8.91), with $a = q$, to prove that

$$(9.110) \quad \mathbf{w}_{\epsilon_m} \rightarrow 0 \quad \text{strongly in } \mathbf{L}^q(\mathbb{R}^{N+1}), \quad \text{as } m \rightarrow \infty.$$

Moreover, using (4.34) and again (8.91) with $a = q$, we obtain

$$(9.111) \quad \|\nabla \mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})} \leq C.$$

On the other hand, due to (4.42) and (8.102), we have

$$(9.112) \quad \|\mathbf{Q}_{\epsilon_m}^1\|_{\mathbf{L}^{q'}(\mathbb{R}^{N+1})} \leq C.$$

Moreover, (5.55) together with (8.103), and (4.46) together with (8.104), justify, respectively, that

$$(9.113) \quad \mathbf{Q}_{\epsilon_m}^2 \rightarrow 0 \quad \text{strongly in } \mathbf{L}^{\frac{q(N+2)}{2N}}(\mathbb{R}^{N+1}), \quad \text{as } m \rightarrow \infty,$$

$$(9.114) \quad \mathbf{q}_{\epsilon_m} \rightarrow 0 \quad \text{strongly in } \mathbf{L}^{\sigma'}(\mathbb{R}^{N+1}), \quad \text{as } m \rightarrow \infty.$$

In order to define the irregularity regions of the admissible function that we shall test in (8.105), let us set

$$(9.115) \quad f_{\epsilon_m} := \mathcal{M}^*(|\mathbf{w}_{\epsilon_m}|),$$

$$(9.116) \quad g_{\epsilon_m} := \mathcal{M}^*(|\nabla \mathbf{w}_{\epsilon_m}|) + (\mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^1|))^{\frac{1}{q-1}},$$

$$(9.117) \quad h_{\epsilon_m} := (\mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^2|))^{\frac{1}{q-1}},$$

$$(9.118) \quad i_{\epsilon_m} := (\mathcal{M}^*(|\mathbf{q}_{\epsilon_m}|))^{\frac{1}{q-1}},$$

where $\mathcal{M}^* := \mathcal{M}_t \circ \mathcal{M}_{\mathbf{x}}$. Here \mathcal{M}_t and $\mathcal{M}_{\mathbf{x}}$ denote the Hardy-Littlewood maximal operators, which are defined, for some function $f \in L^p(\mathbb{R}^{N+1})$ with $1 < p < \infty$, respectively by

$$\begin{aligned} \mathcal{M}_t(f)(\mathbf{x}, t) &:= \sup_{0 < r < \infty} \frac{1}{2r} \int_{t-r}^{t+r} |f(\mathbf{x}, s)| ds, \\ \mathcal{M}_{\mathbf{x}}(f)(\mathbf{x}, t) &:= \sup_{0 < R < \infty} \frac{1}{\mathcal{L}_N(B_R(\mathbf{x}))} \int_{B_R(\mathbf{x})} |f(\mathbf{y}, s)| d\mathbf{y}, \end{aligned}$$

where $B_R(\mathbf{x})$ denotes the ball of \mathbb{R}^N centered at \mathbf{x} and with radius $R > 0$. Then due to the boundedness of the operator \mathcal{M}^* from $\mathbf{L}^p(\mathbb{R}^{N+1})$ into $\mathbf{L}^p(\mathbb{R}^{N+1})$ for any $p > 1$ (see *e.g.* Stein [22, p. 5]), we obtain

$$(9.119) \quad \|f_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})} \leq C \|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})},$$

$$(9.120) \quad \|g_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})} \leq C_1 \|\nabla \mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})} + C_2 \|\mathbf{Q}_{\epsilon_m}^1\|_{\mathbf{L}^{q'}(\mathbb{R}^{N+1})}^{\frac{1}{q-1}},$$

$$(9.121) \quad \|\mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^2|)\|_{\mathbf{L}^{q \frac{N+2}{2N}}(\mathbb{R}^{N+1})} \leq C \|\mathbf{Q}_{\epsilon_m}^2\|_{\mathbf{L}^{q \frac{N+2}{2N}}(\mathbb{R}^{N+1})},$$

$$(9.122) \quad \|\mathcal{M}^*(|\mathbf{q}_{\epsilon_m}|)\|_{\mathbf{L}^{\sigma'}(\mathbb{R}^{N+1})} \leq C \|\mathbf{q}_{\epsilon_m}\|_{\mathbf{L}^{\sigma'}(\mathbb{R}^{N+1})}.$$

Next, let j_{ϵ_m} be anyone of the functions inside the norms on the left-hand sides of (9.119)-(9.122) and let s be the respective Lebesgue exponent. Using (9.111)-(9.114), (9.119)-(9.122) and arguing as in [12, p. 31], we obtain for $j \in \mathbb{N}$

$$\|j_{\epsilon_m}\|_{\mathbf{L}^s(\mathbb{R}^{N+1})}^s \geq 2^j \ln(2) \inf_{2^{2j} \leq \tau \leq 2^{2j+1}} \tau^s \mathcal{L}_{N+1} \left(\{(\mathbf{x}, t) \in \mathbb{R}^{N+1} : |j_{\epsilon_m}| > \tau\} \right).$$

As a consequence, there exists $\lambda_{m,j} \in [2^{2^j}, 2^{2^{j+1}}]$ such that

$$(9.123) \quad \mathcal{L}_{N+1} \left\{ (\mathbf{x}, t) \in \mathbb{R}^{N+1} : |j_{\epsilon_m}| > \lambda_{m,j} \right\} \leq C 2^{-j} \lambda_{m,j}^{-p} \|j_{\epsilon_m}\|_{\mathbf{L}^p(\mathbb{R}^{N+1})}.$$

Let us consider the following subsets of \mathbb{R}^{N+1}

$$(9.124) \quad F_{m,j} := \{(\mathbf{x}, t) : |f_{\epsilon_m}| > \lambda_{m,j}\},$$

$$(9.125) \quad G_{m,j} := \{(\mathbf{x}, t) : |g_{\epsilon_m}| > \lambda_{m,j}\},$$

$$(9.126) \quad H_{m,j} := \{(\mathbf{x}, t) : |h_{\epsilon_m}| > \lambda_{m,j}\} \equiv \left\{ (\mathbf{x}, t) : \mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^2|) > \lambda_{m,j}^{q-1} \right\},$$

$$(9.127) \quad I_{m,j} := \{(\mathbf{x}, t) : |i_{\epsilon_m}| > \lambda_{m,j}\} \equiv \left\{ (\mathbf{x}, t) : \mathcal{M}^*(|\mathbf{q}_{\epsilon_m}|) > \lambda_{m,j}^{q-1} \right\}.$$

Then, using (9.123) in each case separately, we obtain

$$(9.128) \quad \mathcal{L}_{N+1}(F_{m,j}) \leq C 2^{-j} \lambda_{m,j}^{-q} \|f_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})},$$

$$(9.129) \quad \mathcal{L}_{N+1}(G_{m,j}) \leq C 2^{-j} \lambda_{m,j}^{-q} \|g_{\epsilon_m}\|_{\mathbf{L}^q(\mathbb{R}^{N+1})},$$

$$(9.130) \quad \mathcal{L}_{N+1}(H_{m,j}) \leq C 2^{-j} \lambda_{m,j}^{-(q-1)q \frac{N+2}{2N}} \|\mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^2|)\|_{\mathbf{L}^{q \frac{N+2}{2N}}(\mathbb{R}^{N+1})},$$

$$(9.131) \quad \mathcal{L}_{N+1}(I_{m,j}) \leq C 2^{-j} \lambda_{m,j}^{-(q-1)\sigma'} \|\mathcal{M}^*(|\mathbf{q}_{\epsilon_m}|)\|_{\mathbf{L}^{\sigma'}(\mathbb{R}^{N+1})}.$$

Now, since $\lambda_{m,j} \in [2^{2^j}, 2^{2^{j+1}}]$, we observe that (9.110), (9.119) and (9.128) on the one hand, (9.113), (9.121) and (9.130) on the other, and yet (9.114), (9.122) and (9.131) on another one, imply, respectively,

$$(9.132) \quad \limsup_{m \rightarrow \infty} \mathcal{L}_{N+1}(F_{m,j}) = 0, \quad \limsup_{m \rightarrow \infty} \mathcal{L}_{N+1}(H_{m,j}) = 0, \quad \limsup_{m \rightarrow \infty} \mathcal{L}_{N+1}(I_{m,j}) = 0.$$

Moreover, since \mathcal{M}^* is subadditive (see *e.g.* Stein [22]), we get from the definitions of $G_{m,j}$, $H_{m,j}$ and $I_{m,j}$ in (9.125)-(9.127), using (9.129)-(9.131) and (9.116)-(9.118), that

$$(9.133) \quad G_{m,j} \cup H_{m,j} \cup I_{m,j} \supset \mathcal{O},$$

where

$$\mathcal{O} := \{(\mathbf{x}, t) \in \mathbb{R}^{N+1} : \mathcal{M}^*(|\nabla \mathbf{w}_{\epsilon_m}|) + \rho_{m,j} (\mathcal{M}^*(|\mathbf{Q}_{\epsilon_m}^{1,2}|) + \mathcal{M}^*(|\mathbf{q}_{\epsilon_m}|)) < 4\lambda_{m,j}\},$$

$$(9.134) \quad \rho_{m,j} := \lambda_{m,j}^{2-q}$$

and, with the notations of (9.107)-(9.108),

$$(9.135) \quad \mathbf{Q}_{\epsilon_m}^{1,2} := \mathbf{Q}_{\epsilon_m}^1 + \mathbf{Q}_{\epsilon_m}^2.$$

Setting

$$(9.136) \quad E_{m,j} := (F_{m,j} \cup G_{m,j} \cup H_{m,j} \cup I_{m,j}) \cap \omega_T,$$

we can readily see that due to (9.128)-(9.131), (9.119)-(9.122) and to (9.110)-(9.114),

$$(9.137) \quad \mathcal{L}_{N+1}(E_{m,j}) < \infty.$$

Moreover, due to (9.133), we have

$$(9.138) \quad (\mathcal{O} \cup \mathcal{U}) \cap \omega_T \subset E_{m,j} \subset \omega_T,$$

where here \mathcal{U} is the set $F_{m,j}$ defined in (9.124).

10. CONSTRUCTION OF A LIPSCHITZ TRUNCATION

We are now in conditions to define the truncation we shall consider here. Let us consider the following family of cubes

$$(10.139) \quad \mathcal{C}_{r_n}^{\rho_{m,j}}(\mathbf{x}_n, t_n) := \{(\mathbf{y}, s) \in \mathbb{R}^{N+1} : d_{\rho_{m,j}}((\mathbf{x}_n, t_n), (\mathbf{y}, s)) < r_n\},$$

where $r_n > 0$, $n \in \mathbb{N}$ and $d_{\rho_{m,j}}$ is the metric defined by

$$(10.140) \quad d_{\rho_{m,j}}((\mathbf{x}_n, t_n), (\mathbf{y}, s)) := \max \left\{ |\mathbf{y} - \mathbf{x}_n|, \sqrt{\rho_{m,j}^{-1} |s - t_n|} \right\}.$$

By [22, Theorem VI.1.1]), there exists a Whitney covering of $E_{m,j}$ formed by the family of cubes (10.139)-(10.140) such that

$$\bigcup_{n \in \mathbb{N}} \mathcal{C}_{\frac{1}{2}r_n}^{\rho_{m,j}}(\mathbf{x}_n, t_n) = E_{m,j}.$$

Moreover, by [22, Section VI.1.3], there exists a partition of unity ψ_n , $n \in \mathbb{N}$, associated to the Whitney covering (10.139)-(10.140) such that

$$\sum_{k \in \mathbb{N}} \psi_k = 1 \quad \text{in } \mathcal{C}_{r_n}^{\rho_{m,j}}(\mathbf{x}_n, t_n).$$

We are now in conditions to define the Lipschitz truncation. Following [12, Section 3] and [22, Chapter VI], we define the Lipschitz truncation of \mathbf{w}_{ϵ_m} subordinated to the Whitney covering (10.139)-(10.140) by

$$(10.141) \quad \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) := \begin{cases} \mathbf{w}_{\epsilon_m} & \text{in } \omega_T \setminus E_{m,j}, \\ \sum_{n=1}^{\infty} \psi_n \mathbf{w}_{\epsilon_m} |_{\mathcal{C}_{r_n}^{\rho_{m,j}}(\mathbf{x}_n, t_n)} & \text{in } E_{m,j}. \end{cases}$$

The idea of this truncation, is to regularize the function \mathbf{w}_{ϵ_m} by cutting off the regions $E_{m,j}$ of irregularity and then to extend this restricted function by the Whitney covering (10.139)-(10.140) to the whole domain again.

Now, let $\xi \in C_0^\infty(\omega_T)$ be a fixed cut-off function such that $0 \leq \xi \leq 1$ in ω_T and let us consider the following admissible test function for (8.105)

$$(10.142) \quad \phi_{m,j} := \xi \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}).$$

In order to establish the main properties of the Lipschitz truncation (10.141) we are interested in, let

$$(10.143) \quad \omega_T^\xi := \text{supp } \xi, \quad \xi \text{ is the cut-off function of (10.142).}$$

Note that ω_T^ξ is strictly contained in ω_T , because $0 \leq \xi \leq 1$ in ω_T . Let also $\mathbf{C}_{\rho_{m,j}}^{0,1}(\omega_T^\xi)$ be the space of all Lipschitz continuous functions with respect to the metric (10.140). From the definition of \mathbf{w}_{ϵ_m} (see (9.106)), using (4.34) and (6.56) together with (8.91), with $a = q$, and (8.88), we can prove that

$$\mathbf{w}_{\epsilon_m} \in L^\infty(0, T; \mathbf{L}^2(\omega)) \cap L^q(0, T; \mathbf{W}^{1,q}(\omega)).$$

Then, owing to (9.132)-(9.138), we can apply directly [12, Theorem 3.9, (i)-(iii)] to obtain:

$$(10.144) \quad \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \in \mathbf{C}_{\rho_{m,j}}^{0,1}(\omega_T^\xi),$$

with the norm depending on N , ω_T^ξ , $\|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^1(E_{m,j})}$, $\|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^1(\tilde{\omega}_T)}$, where $\omega_T^\xi \subset \subset \tilde{\omega}_T \subset \subset \omega_T$;

$$(10.145) \quad \|\nabla \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} \leq C \left(\lambda_{m,j} + \rho_{m,j}^{-1} \delta_{\rho_{m,j}, \omega_T^\xi}^{-N-3} \|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^1(E_{m,j})} \right);$$

$$(10.146) \quad \|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} \leq C \left(1 + \rho_{m,j}^{-1} \delta_{\rho_{m,j}, \omega_T^\xi}^{-N-2} \|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^1(E_{m,j})} \right);$$

$$(10.147) \quad \begin{aligned} & \|(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}))' \cdot (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) - (\mathbf{w}_{\epsilon_m}))\|_{\mathbf{L}^1(\omega_T^\xi \cap E_{m,j})} \leq \\ & C \rho_{m,j}^{-1} \mathcal{L}_{N+1}(E_{m,j}) \left(\lambda_{m,j} + \rho_{m,j}^{-1} \delta_{\rho_{m,j}, \omega_T^\xi}^{-N-3} \|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^1(E_{m,j})} \right)^2. \end{aligned}$$

In (10.145)-(10.147) the constants C are distinct and depend only on N , and

$$(10.148) \quad \delta_{\rho_{m,j}, \omega_T^\xi} := d_{\rho_{m,j}}(\omega_T^\xi, \omega_T) > 0 \quad \text{due to (10.143).}$$

Moreover, according to [12, Lemma 3.5] (see also [22, Section VI.3]),

$$(10.149) \quad \|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^s(\omega_T)} \leq C \|\mathbf{w}_{\epsilon_m}\|_{\mathbf{L}^s(\omega_T)} \quad \forall s : 1 \leq s \leq \infty,$$

where C depends only on N .

11. CONVERGENCE OF THE APPROXIMATED EXTRA STRESS TENSOR

Proceeding as for (8.105), observing that now the functions are zero outside ω_T and using the notations (9.135) and (9.106)-(9.109), we obtain

$$(11.150) \quad \mathbf{w}'_{\epsilon_m} = -\mathbf{div} \mathbf{Q}_{\epsilon_m}^{1,2} - \mathbf{q}_{\epsilon_m} \quad \text{in } \mathcal{D}'(\omega_T)$$

Here the distributive time derivative \mathbf{w}'_{ϵ_m} is such that

$$(11.151) \quad \mathbf{w}'_{\epsilon_m} \in \mathbf{L}^{r_0}(0, T; \mathbf{W}^{-1, r_0}(\omega)) + \mathbf{L}^{\sigma'}(\omega_T),$$

where r_0 is defined by (8.83). In fact, due to (4.42), (5.55), (8.102) and (8.103) on one hand, and due to (4.46) and (8.104) on the other, we can prove that

$$(11.152) \quad \mathbf{Q}_{\epsilon_m}^{1,2} \in \mathbf{L}^{r_0}(\omega_T) \quad \text{and} \quad \mathbf{q}_{\epsilon_m} \in \mathbf{L}^{\sigma'}(\omega_T).$$

As a consequence of (11.152)₁, $\mathbf{div} \mathbf{Q}_{\epsilon_m}^{1,2} \in \mathbf{L}^{r_0}(0, T; \mathbf{W}^{-1, r_0}(\omega))$. Now, observing that, by virtue of (10.144)-(10.146) and of the definition of ξ , our admissible test function, defined in (10.142), $\phi_{m,j} \in \mathbf{L}^{r'_0}(0, T; \mathbf{W}_0^{1, r'_0}(\omega)) \cap \mathbf{L}^{\sigma}(\omega_T)$. Then, from (11.150) and (11.151), we infer that

$$(11.153) \quad \int_0^T \langle \mathbf{w}'_{\epsilon_m}(t), \phi_{m,j}(t) \rangle dt = \int_{\omega_T} \mathbf{Q}_{\epsilon_m}^{1,2} : \nabla \phi_{m,j} d\mathbf{x} dt - \int_{\omega_T} \mathbf{q}_{\epsilon_m} \cdot \phi_{m,j} d\mathbf{x} dt.$$

On the other hand, owing to (9.132)-(9.138) and, in addition, to (11.152)-(11.153), we can apply [12, Theorem 3.9, (iv)] to prove that for every $\xi \in \mathbf{C}_0^{\infty}(\omega_T)$

$$(11.154) \quad \begin{aligned} & \int_0^T \langle \mathbf{w}'_{\epsilon_m}(t), \phi_{m,j}(t) \rangle dt = \\ & \frac{1}{2} \int_{\omega_T} \left(|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})|^2 - 2\mathbf{w}_{\epsilon_m} \cdot \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \right) \xi' d\mathbf{x} dt + \\ & \int_{E_{m,j}} (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}))' \cdot (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) - \mathbf{w}_{\epsilon_m}) \xi d\mathbf{x} dt. \end{aligned}$$

Note that the proof of (11.154) is done in [12, p. 23] for $\mathbf{q}_{\epsilon_m} \equiv 0$ in (11.153). But taking into account (11.151), the proof of [12, Theorem 3.9, (iv)] can be repeated almost word by word in our case.

Now, gathering (11.153) and (11.154), and expanding the notations (9.135) and (9.106)-(9.109), we obtain

$$\begin{aligned}
& \int_{\omega_T} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})) \xi \, d\mathbf{x} dt = \\
& + \int_{\omega_T} (\mathbf{S} - |\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m}) : \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \otimes \nabla \xi \, d\mathbf{x} dt \\
& + \int_{\omega_T} (\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}) : \nabla (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi) \, d\mathbf{x} dt \\
& + \alpha \int_{\omega_T} (|\mathbf{u}|^{\sigma-2} \mathbf{u} - |\mathbf{u}_{\epsilon_m}|^{\sigma-2} \mathbf{u}_{\epsilon_m}) \cdot \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi \, d\mathbf{x} dt \\
& + \int_{\omega_T} p_{\epsilon_m}^1 \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \cdot \nabla \xi \, d\mathbf{x} dt \\
(11.155) \quad & + \int_{\omega_T} p_{\epsilon_m}^1 \operatorname{div}(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})) \xi \, d\mathbf{x} dt \\
& + \int_{\omega_T} p_{\epsilon_m}^2 \operatorname{div}(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi) \, d\mathbf{x} dt \\
& - \int_{\omega_T} \nabla p_{\epsilon_m}^3 \cdot \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi \, d\mathbf{x} dt \\
& + \frac{1}{2} \int_{\omega_T} \left(2\mathbf{w}_{\epsilon_m} \cdot \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) - |\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})|^2 \right) \xi' \, d\mathbf{x} dt \\
& + \int_{E_{m,j}} \mathcal{T}'_{m,j}(\mathbf{w}_{\epsilon_m}) \cdot (\mathbf{w}_{\epsilon_m} - \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})) \xi \, d\mathbf{x} dt \\
& := J_1 + J_2 + J_3 + J_4 + J_5 + J_6 + J_7 + J_8 + J_9.
\end{aligned}$$

We claim that, for a fixed j ,

$$(11.156) \quad \limsup_{m \rightarrow \infty} \left| \int_{\omega_T} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla (\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})) \xi \, d\mathbf{x} dt \right| \leq C 2^{-\frac{j}{q}}.$$

To prove this, we will carry out the passage to the limit $m \rightarrow \infty$ in all absolute values $|J_i|$, $i = 1, \dots, 9$.

• $\limsup_{m \rightarrow \infty} (|J_1| + |J_4|) = 0$. Due to (4.42) and (8.102), $\mathbf{S} - |\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m}$ and $p_{\epsilon_m}^1$ are uniformly bounded in $\mathbf{L}^{q'}(\omega_T)$. Then, using Hölder's inequality and (10.149) together with (9.106), led us to

$$|J_1| + |J_4| \leq C_1 \|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^q(\omega_T)} \leq C_2 \left(\|\mathbf{u}_{\epsilon_m} - \mathbf{u}\|_{\mathbf{L}^q(\omega_T)} + \|\nabla(\tilde{p}_{\epsilon_m}^h - \tilde{p}^h)\|_{\mathbf{L}^q(\omega_T)} \right).$$

The assertion follows by the application of (5.54) with $s = \gamma = q$ and (8.91) with $a = q$, and observing that always $q < q^*$ for any $q \geq 1$.

• $\limsup_{m \rightarrow \infty} (|J_2| + |J_6|) = 0$. In fact, by Hölder's inequality,

$$\begin{aligned}
|J_2| + |J_6| & \leq \|\mathbf{u}_{\epsilon_m} \otimes \mathbf{u}_{\epsilon_m} \Phi_{\epsilon_m}(|\mathbf{u}_{\epsilon_m}|) - \mathbf{u} \otimes \mathbf{u}\|_{\mathbf{L}^1(\omega_T)} \|\nabla(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi)\|_{\mathbf{L}^\infty(\omega_T^\xi)} + \\
& \quad \|p_{\epsilon_m}^2\|_{\mathbf{L}^1(\omega_T)} \|\operatorname{div}(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi)\|_{\mathbf{L}^\infty(\omega_T^\xi)}.
\end{aligned}$$

Then, using Hölder's inequality again and due to (5.55) and (8.103), we get $\limsup_{m \rightarrow \infty} (|J_2| + |J_6|) = 0$ if both second multiplying terms on the right-hand side of the above inequality are finite. Indeed, by the application of (10.145) and

(10.146) together with (9.106), we get

$$\begin{aligned} & \|\nabla(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\xi)\|_{\mathbf{L}^\infty(\omega_T^\xi)} \leq \\ & \|\nabla\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} + C\|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} \leq \\ & C_1 \left(\lambda_{m,j} + \frac{\|\mathbf{v}_{\epsilon_m} - \mathbf{v}\|_{\mathbf{L}^1(E_{m,j})}}{\rho_{m,j}\delta_{\rho_{m,j},\omega_T^\xi}^{N+3}} \right) + C_2 \left(1 + \frac{\|\mathbf{v}_{\epsilon_m} - \mathbf{v}\|_{\mathbf{L}^1(E_{m,j})}}{\rho_{m,j}\delta_{\rho_{m,j},\omega_T^\xi}^{N+2}} \right). \end{aligned}$$

From (4.40) and (8.91), the last with $a = q$, $\mathbf{v}_{\epsilon_m} - \mathbf{v}$ is uniformly bounded in $\mathbf{L}^1(E_{m,j})$. On the other hand, for a fixed $j \in \mathbb{N}$, the sequence $\lambda_{m,j}$ lies in the interval $[2^{2^j}, 2^{2^{j+1}}]$ and, as a consequence, the sequence $\rho_{m,j} = \lambda_{m,j}^{2-q}$ is uniformly bounded from above, which, in turn, by (10.148) and (10.140), implies

$$\inf_{m \in \mathbb{N}} \delta_{\rho_{m,j},\omega_T^\xi} > 0.$$

Analogously, we prove that also $\|\operatorname{div}(\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\xi)\|_{\mathbf{L}^\infty(\omega_T^\xi)}$ is finite.

• $\limsup_{m \rightarrow \infty} (|J_3| + |J_7|) = 0$. By Hölder's inequality and (8.104)

$$\begin{aligned} |J_3| + |J_7| & \leq (\alpha\||\mathbf{u}_{\epsilon_m}|^{\sigma-2}\mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2}\mathbf{u}\|_{\mathbf{L}^1(\omega_T)} + \|\nabla p_{\epsilon_m}^3\|_{\mathbf{L}^1(\omega_T)}) \|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} \\ & \leq C\||\mathbf{u}_{\epsilon_m}|^{\sigma-2}\mathbf{u}_{\epsilon_m} - |\mathbf{u}|^{\sigma-2}\mathbf{u}\|_{\mathbf{L}^{\sigma'}(\omega_T)} \|\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)}. \end{aligned}$$

Arguing as in the previous case, we can show that, for each $j \in \mathbb{N}$, $\mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})$ is uniformly bounded in $\mathbf{L}^\infty(\omega_T^\xi)$. Then, by the application of (4.46), it follows that $\limsup_{m \rightarrow \infty} (|J_3| + |J_7|) = 0$.

• $\limsup_{m \rightarrow \infty} (|J_5| + |J_9|) \leq C2^{-\frac{j}{q}}$. By the definition of the Lipschitz truncation (see (10.141)) together with the fact that $\operatorname{div}\mathbf{w}_{\epsilon_m} = 0$ (see (9.106)), we can write

$$J_5 = \int_{\omega_T^\xi \cap E_{m,j}} p_{\epsilon_m}^1 \operatorname{div} \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) d\mathbf{x} dt.$$

Next we use Hölder's inequality, (4.42) and (8.102) together with (10.145). Then, arguing as in the cases for $|J_1| + |J_4|$ and $|J_2| + |J_6|$, we have

$$\begin{aligned} \limsup_{m \rightarrow \infty} |J_5| & \leq C_1 \limsup_{m \rightarrow \infty} \|\nabla \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^q(\omega_T^\xi \cap E_{m,j})} \\ & \leq C_1 \limsup_{m \rightarrow \infty} \mathcal{L}_{N+1}(E_{m,j})^{\frac{1}{q}} \|\nabla \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m})\|_{\mathbf{L}^\infty(\omega_T^\xi)} \\ & \leq C_2 \limsup_{m \rightarrow \infty} \left[\mathcal{L}_{N+1}(E_{m,j})^{\frac{1}{q}} \left(\lambda_{m,j} + \frac{\|\mathbf{v}_{\epsilon_m} - \mathbf{v}\|_{\mathbf{L}^1(E_{m,j})}}{\rho_{m,j}\delta_{\rho_{m,j},\omega_T^\xi}^{N+3}} \right) \right] \\ & \leq C_2 \limsup_{m \rightarrow \infty} \left(\mathcal{L}_{N+1}(E_{m,j})^{\frac{1}{q}} \lambda_{m,j} \right). \end{aligned}$$

Next, by the definition of $E_{m,j}$ (see (9.136)) and using (9.132), (9.129), (9.120) and (9.111)-(9.112) by this order, we get $\limsup_{m \rightarrow \infty} |J_5| \leq C2^{-\frac{j}{q}}$.

For J_9 , we have by using (10.147) together with the definition of $\rho_{m,j}$ (see (9.134)) and arguing as we did above for $|J_5|$,

$$\begin{aligned} \limsup_{m \rightarrow \infty} |J_9| &\leq C \limsup_{m \rightarrow \infty} \left[\lambda_{m,j}^{q-2} \mathcal{L}_{N+1}(E_{m,j}) \left(\lambda_{m,j} + \frac{\|\mathbf{v}_{\epsilon_m} - \mathbf{v}\|_{\mathbf{L}^1(E_{m,j})}}{\rho_{m,j} \delta_{\rho_{m,j}, \omega_T}^{\frac{N+3}{2}}} \right)^2 \right] \\ &\leq C \limsup_{m \rightarrow \infty} \left(\lambda_{m,j}^{q-1} \mathcal{L}_{N+1}(E_{m,j}) \right) \\ &\leq C 2^{-j}. \end{aligned}$$

Then observing that $q > 1$, it follows that $\limsup_{m \rightarrow \infty} |J_9| \leq C 2^{-\frac{j}{q}}$.

Throughout the above bullets, we have proven the claim (11.156) is true. On the other hand, arguing as we did for $|J_5|$, we can prove also that, for a fixed j ,

$$(11.157) \quad \limsup_{m \rightarrow \infty} \left| \int_{E_{m,j}} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla \mathcal{T}_{m,j}(\mathbf{w}_{\epsilon_m}) \xi \, d\mathbf{x} dt \right| \leq C 2^{-\frac{j}{q}}.$$

In consequence, from the definition of $\mathcal{T}_{m,j}$ (see (10.141)), (11.156) and (11.157), we prove that

$$(11.158) \quad \limsup_{m \rightarrow \infty} \left| \int_{\omega_T \setminus E_{m,j}} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla \mathbf{w}_{\epsilon_m} \xi \, d\mathbf{x} dt \right| \leq C 2^{-\frac{j}{q}}.$$

Using the definition of \mathbf{w}_{ϵ_m} (see (9.106)) and the strong convergence property of $\tilde{p}_{\epsilon_m}^h$ (see (8.91)), it can be derived from (11.158) that

$$(11.159) \quad \limsup_{m \rightarrow \infty} \left| \int_{\omega_T \setminus E_{m,j}} (|\nabla \mathbf{u}_{\epsilon_m}|^{q-2} \nabla \mathbf{u}_{\epsilon_m} - \mathbf{S}) : \nabla (\mathbf{u}_{\epsilon_m} - \mathbf{u}) \xi \, d\mathbf{x} dt \right| \leq C 2^{-\frac{j}{q}}.$$

Now, by (11.159) and (9.132), for each $j \in \mathbb{N}$ we can find a number $m_j \in \mathbb{N}$ such that

$$(11.160) \quad \left| \int_{\omega_T \setminus E_{m_j,j}} (|\nabla \mathbf{u}_{\epsilon_{m_j}}|^{q-2} \nabla \mathbf{u}_{\epsilon_{m_j}} - \mathbf{S}) : \nabla (\mathbf{u}_{\epsilon_{m_j}} - \mathbf{u}) \xi \, d\mathbf{x} dt \right| \leq C 2^{-\frac{j}{q}},$$

$$(11.161) \quad \mathcal{L}_{N+1}(F_{m_j,j}) \leq C 2^{-j},$$

$$(11.162) \quad \mathcal{L}_{N+1}(H_{m_j,j}) \leq C 2^{-j},$$

$$(11.163) \quad \mathcal{L}_{N+1}(I_{m_j,j}) \leq C 2^{-j}.$$

Setting $\xi_j := \xi \chi_{\omega_T \setminus E_{m_j,j}}$, where $\chi_{\omega_T \setminus E_{m_j,j}}$ denotes the characteristic function of the set $\omega_T \setminus E_{m_j,j}$, it can be proved (cf. [12, pp. 36-37]), using (9.129), (11.161)-(11.163) and the fact that $\lambda_{m_j,j} \geq 1$, that

$$(11.164) \quad \xi_j \rightarrow \xi \quad \text{a.e. in } \omega_T \quad \text{as } j \rightarrow \infty.$$

From (11.164), (4.40) and (4.42), we have, by appealing to Lebesgue's theorem of dominated convergence, that

$$(11.165) \quad \nabla \mathbf{u} \xi_j \rightarrow \nabla \mathbf{u} \xi \quad \text{strongly in } \mathbf{L}^q(\omega_T), \quad \text{as } j \rightarrow \infty,$$

$$(11.166) \quad \mathbf{S} \xi_j \rightarrow \mathbf{S} \xi \quad \text{strongly in } \mathbf{L}^{q'}(\omega_T), \quad \text{as } j \rightarrow \infty.$$

Then, from (11.160) and (11.165)-(11.166), and appealing once more to (4.40), (4.42) and Lebesgue's theorem of dominated convergence, we obtain

$$(11.167) \quad \lim_{j \rightarrow \infty} \int_{\omega_T} |\nabla \mathbf{u}_{\epsilon_m_j}|^q \xi_j \, dxdt = \int_{\omega_T} \mathbf{S} : \nabla \mathbf{u} \xi \, dxdt.$$

Finally, taking into account (4.40), (4.42), (11.164) and (11.167), we can apply the local Minty trick (*cf.* [24, Lemma A.2]) to establish that $\mathbf{S} \xi = |\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u} \xi$ a.e. in ω_T . Due to the arbitrariness of ξ , $\mathbf{S} = |\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u}$ a.e. in ω_T and the proof of Theorem 2.1 is concluded. \blacksquare

12. REMARKS

In Theorem 2.1 we have proved the existence of weak solutions, in the sense of Definition 2.1, to the problem (1.1)-(1.4) for any

$$q > \frac{2N}{N+2} \quad \text{and} \quad \sigma > 1.$$

It is only left open the case of $1 < q \leq \frac{2N}{N+2}$ for $N \geq 3$. But with the methods at our present disposal it seems to be very difficult to prove this case, because the compact imbedding $W^{1,q}(\Omega) \hookrightarrow \hookrightarrow L^2(\Omega)$, which holds only for $q > \frac{2N}{N+2}$, is fundamental in many steps of our proof.

The result established in Theorem 2.1 is still valid if we consider an extra stress tensor with a q -structure satisfying to general growth and coercivity conditions. Indeed the proof still holds with minor changes if we assume that the diffusion term $|\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u}$ in (1.2) is replaced by a tensor $\mathbf{T} \equiv \mathbf{T}(\mathbf{x}, t, \mathbf{D})$ (\mathbf{D} is the symmetric part of $\nabla \mathbf{u}$) satisfying to

- $|\mathbf{T}(\mathbf{x}, t, \mathbf{A})| \leq C_1 |\mathbf{A}|^{q-1} + f_1$ for all \mathbf{A} in $\mathbb{M}_{\text{sym}}^n$, for a.a. (\mathbf{x}, t) in Q_T and for any function f_1 in $L^{q'}(Q_T)$ with $f_1 \geq 0$;
- $\mathbf{T}(\mathbf{x}, t, \mathbf{A}) : \mathbf{A} \geq C_2 |\mathbf{A}|^q - f_2$ for all \mathbf{A} in $\mathbb{M}_{\text{sym}}^n$, for a.a. (\mathbf{x}, t) in Q_T and for any function f_2 in $L^1(Q_T)$ with $f_2 \geq 0$;

where C_1 and C_2 denote positive constants and $\mathbb{M}_{\text{sym}}^n$ is the vector space of all symmetric $n \times n$ matrices, which is equipped with the scalar product $\mathbf{A} : \mathbf{B}$ and norm $|\mathbf{A}| = \sqrt{\mathbf{A} : \mathbf{A}}$.

It is possible to consider unbounded domains with no restriction on the size and shape of Ω . In this case, proceeding as in [24, Section 3], we can prove the regularized problem (3.14)-(3.17) has a unique weak solution for such Ω . As a consequence the original problem has a solution for these domains as well.

The uniqueness of weak solutions is, as is well known, an open problem for the generalized Navier-Stokes problem (without damping) for values of $q \leq 2$. By adapting [17, Théorème 2.5.2], we can prove the weak solution to the problem (1.1)-(1.4) is unique under more restrictive conditions that we have needed to prove the existence. In fact, assuming that $q \geq \frac{N+2}{N}$, replacing the diffusion term $\mathbf{div} (|\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u})$ in (1.2) by $\mathbf{div} (|\nabla \mathbf{u}|^{q-2} \nabla \mathbf{u}) + \Delta \mathbf{u}$ and having in mind the damping term satisfies to (2.5), it is possible to prove the uniqueness of weak solution to this modified problem (1.1)-(1.4) (see [18, Theorem 2]).

A completely different issue, is the important question about the qualitative properties of the weak solutions to the problem (1.1)-(1.4). In this scope we are mainly interested in the extinction in a finite time, once that the confinement of the weak solutions in a space domain is a much more delicate matter and remains

an open problem, with the exceptions of the stationary Stokes and Navier-Stokes problems (*cf.* [1]–[4] and [18]). Proceeding as in [18, Theorem 3], letting \mathbf{u} be a weak solution to the problem (1.1)–(1.4) in the sense of Definition 2.1 and assuming that (2.10) and one of the following conditions hold:

- (1) $q < 2$; or
- (2) $1 < \sigma < 2$;

then we can prove the following assertions are true with minor changes in the proofs:

- If $\mathbf{f} = \mathbf{0}$ a.e. in Q_T , then there exists $t_{(i)}^* > 0$ such that $\mathbf{u}(\mathbf{x}, t) = \mathbf{0}$ a.e. in Ω and for all $t \geq t_{(i)}^*$, for $i = 1, 2$;
- Let $\mathbf{f} \neq \mathbf{0}$ and assume that exist positive constants $\epsilon_{(i)}$ and (positive) times $t_{(i)}^{\mathbf{f}}$, for $i = 1, 2$, such that, for almost all $t \in [0, T]$,

$$\|\mathbf{f}(t)\|_{\mathbf{L}^{q'}(\Omega)} \leq \epsilon_{(1)} \left(1 - \frac{t}{t_{(1)}^{\mathbf{f}}}\right)_+^{\theta_{(1)}} \quad \text{if } \frac{Nq}{N-q} \leq q < 2, \quad \theta_{(1)} = \frac{q-1}{2-q},$$

or

$$\|\mathbf{f}(t)\|_{\mathbf{L}^{q'}(\Omega)} \leq \epsilon_{(2)} \left(1 - \frac{t}{t_{(2)}^{\mathbf{f}}}\right)_+^{\theta_{(2)}} \quad \text{if } 1 < \sigma < 2, \quad \theta_{(2)} = \frac{(q-1)[q(N+\sigma)-N\sigma]}{q^2(2-\sigma)}.$$

Then there, there exist positive constants $\epsilon_{(i)}^0$ such that $\mathbf{u} = \mathbf{0}$ a.e. in Ω and for all $t \geq t_{(i)}^{\mathbf{f}}$ provided $0 < \epsilon_{(i)} < \epsilon_{(i)}^0$, for $i = 1, 2$.

Note that the subscripts (i) are used above in the sense to relate each result to the different condition (i) written before.

REFERENCES

- [1] S.N. Antontsev, J.I. Díaz and H.B. de Oliveira. On the confinement of a viscous fluid by means of a feedback external field. *C. R. Méc. Acad. Sci. Paris*, **330** (2002), 797–802.
- [2] S.N. Antontsev, J.I. Díaz and H.B. de Oliveira. Stopping a viscous fluid by a feedback dissipative field. I. The stationary Stokes problem. *J. Math. Fluid Mech.* **6** (2004), no. 4, 439–461.
- [3] S.N. Antontsev, J.I. Díaz and H.B. de Oliveira. Stopping a viscous fluid by a feedback dissipative field. II. The stationary Navier-Stokes problem. *Atti Accad. Naz. Lincei Cl. Sci. Fis. Mat. Natur. Rend. Lincei (9) Mat. Appl.* **15** (2004), no. 3–4, 257–270.
- [4] S.N. Antontsev and H.B. de Oliveira. The Navier-Stokes problem modified by an absorption term. *Appl. Anal.* **89** (2010), no. 12, 1805–1825.
- [5] S.N. Antontsev and H.B. de Oliveira. The Oberbeck-Boussinesq problem modified by thermo-absorption term. *J. Math. Anal. Appl.* **379** (2011) no. 2, 802–817.
- [6] J.W. Barret and W.B. Liu. Finite element approximation of the parabolic p -laplacian. *SIAM J. Numer. Anal.* (2) **31** (1994), 413–428.
- [7] H.-O. Bae. Existence, regularity, and decay rate of solutions of non-Newtonian flow. *J. Math. Anal. Appl.* **231** (1999), no. 2, 467–491.
- [8] Ph. Benilan, H. Brezis and M. Crandall. A semilinear equation in $L^1(\mathbb{R}^N)$. *Ann. Scuola Norm. Sup. Pisa Cl. Sci. (4)* **2** (1975), no. 4, 523–555.
- [9] F. Bernis. Elliptic and parabolic semilinear problems without conditions at infinity. *Arch. Rational Mech. Anal.* **106** (1989), 217–241.
- [10] X. Cai and Q. Jiu. Weak and strong solutions for the incompressible Navier-Stokes equations with damping. *J. Math. Anal. Appl.* **343** (2008), no. 2, 799–809.
- [11] R. Carles and C. Gallo. *Finite time extinction by nonlinear damping for the Schrödinger equation*. *Comm. Partial Differential Equations* **36** (2011), no. 6, 961–975.
- [12] L. Diening, M. Růžička and J. Wolf. Existence of weak solutions for unsteady motions of generalized Newtonian fluids. *Ann. Scuola Norm. Sup. Pisa Cl. Csi.* **5**, IX (2010), 1–46.
- [13] J. Frehse, J. Málek and M. Steinhauer. An existence result for fluids with shear dependent viscosity-steady flows. *Nonlinear Anal.* **30** (1997), no. 5, 3041–3049.

- [14] J. Frehse, J. Málek and M. Steinhauer. On analysis of steady flows of fluids with shear dependent viscosity based on the Lipschitz truncation method. *SIAM J. Math. Anal.* **34** (2003), no.5, 1064–1083.
- [15] G.P. Galdi. *An introduction to the mathematical theory of the Navier-Stokes equations. Vol. I. Linearized steady problems.* Springer Tracts in Natural Philosophy, **38**. Springer-Verlag, New York, 1994.
- [16] O.A. Ladyzhenskaya. New equations for the description of motion of viscous incompressible fluids and solvability in the large of boundary value problem for them. *Proc. Steklov Inst. Math.* **102** (1967), 95–118.
- [17] J.-L. Lions. *Quelques méthodes de résolution des problèmes aux limites non linéaires.* Dunod, Paris, 1969.
- [18] H.B. de Oliveira. On the influence of an absorption term in incompressible fluid flows. In *Advances in Mathematical Fluid Mechanics*, Springer-Verlag (2010), 409–424.
- [19] R. Pan and K. Zhao. The 3D compressible Euler equations with damping in a bounded domain. *J. Differential Equations* **246** (2009), no. 2, 581–596.
- [20] A new approach to the Helmholtz decomposition and the Neumann problem in L^q -spaces for bounded and exterior domains. Mathematical problems relating to the Navier-Stokes equation, 1–35. *Ser. Adv. Math. Appl. Sci.* **11**, World Sci. Publ., River Edge, NJ, 1992.
- [21] J. Simon. Compact sets in the space $L^p(0, T; B)$. *Ann. Mat. Pura Appl.* **146** (1987), no. 4, 65–96.
- [22] E.M. Stein. *Singular Integrals and Differentiability Properties of Functions.* Princeton University Press, 1970
- [23] C. Truesdell. Precise theory of the absorption and dispersion of forced plane infinitesimal waves according to the Navier-Stokes equations. *J. Rational Mech. Anal.* **2** (1953). 643–741.
- [24] J. Wolf. Existence of weak solutions to the equations of non-stationary motion of non-Newtonian fluids with shear rate dependent viscosity. *J. Math. Fluid Mech.* **9** (2007), no. 1, 104–138.
- [25] V. Zhikov. New approach to the solvability of generalized Navier-Stokes equations. *Funct. Anal. Appl.* **43**, no. 3 (2009), 190–207.
- [26] Y. Zhou. Global existence and nonexistence for a nonlinear wave equation with damping and source terms. *Math. Nachr.* **278** (2005), no. 11, 1341–1358.